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AN INVESTIGATION OF AIR-ENTRAINMENT  
IN CONCRETE  
AND ITS AFFECT ON DURABILITY

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T H E S I S

AN INVESTIGATION OF AIR-ENTRAINMENT IN CONCRETE  
AND ITS AFFECT ON DURABILITY

Submitted as the Partial Fulfillment  
of the  
Requirements for the Degree of  
Master of Science

by

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Under the direction of  
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University of Alberta  
Edmonton, Alberta.

April 8, 1948

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K. R. Lauer



1948

#13



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## INTRODUCTION

The desire of the concrete industry in general to obtain as dense a concrete mixture as possible because of the resulting high strengths and imperviousness, which in turn made the concrete more durable, delayed the use of air-entrained concrete mixtures. Even when the beneficial effects of entrained air on resistance to freezing and thawing were recognized, the accompanying reductions in density and possible losses in strength were deemed sufficient reason to discontinue work on the subject. In recent years, interest in the possibility of increasing concrete durability by means of air entrainment has been revived largely because of the scaling effects of  $\text{CaCl}_2$  used to remove ice from pavement surfaces. Structural concrete, unlike highway concrete, is seldom if ever exposed to the disintegrating effect of  $\text{CaCl}_2$ . It is, however, very frequently exposed to alternate cycles of freezing and thawing in the presence of excess moisture. It is important therefore to be able to distinguish between durability as measured by freezing and thawing in the presence of chlorides and durability as measured by freezing and thawing in plain water.

The effect of entrained air on resistance to freezing and thawing seems to be independent of the means employed to entrain the added air. One of many different air entraining agents including fatty acids, wetting agents, oils, resins, and chemical compounds can be used. The beneficial effect of the air entrained by such agents on resistance to freezing and thawing of concrete is general, but the changes in strength and density of concretes do vary considerably with the type and amount of agent used. Proper dispersion of the air is required for it to be beneficial. It is generally accepted that the minimum additional air required to increase materially the resistance to freezing and thawing is 3 percent of the volume of the concrete. The entrainment of more air gives additional



increases in resistance, but this added improvement is of doubtful value because of the resulting lower densities and possible losses in strength.

In the investigation to be reported in this paper the effect of entrained air on the durability of concrete was evaluated by the use of an automatic freeze-thaw unit and by  $\text{CaCl}_2$  scaling tests.

The effect of the cycles of freezing and thawing on the concrete were determined by use of the sonic test in which the modulus of elasticity of the concrete was obtained dynamically. Scaling tests were used to determine the resistance of air-entrained concrete to scaling caused by the use of  $\text{CaCl}_2$  for ice removal. An air meter was designed to determine the air content of the mixes used. The effect of the entrained air on the strength of the concrete was evaluated by cylinder tests and beam flexural tests.



## PART I LABORATORY EQUIPMENT

## CHAPTER I

PRESSURE AIR METERIntroduction

The amount of air entrained by air-entraining agents in concrete is of major importance. If too little air is entrained in the concrete the full potential benefits of air entrainment are not realized; if too much air is entrained serious losses in strength will result.

For many years determinations of the air content of fresh concrete have been made by the so-called "gravimetric method" (A.S.T.M. C138-44). In this method the sum of the absolute volumes of the ingredients in a known volume of concrete is calculated and subtracted from the known volume, the difference being taken as the volume of air in the concrete. The accuracy of this method depends upon the accuracy of a series of measurements and assumptions as follows.

(a) Weight per cubic foot of fresh concrete. This measurement is dependent on the accuracy of the sampling, uniformity of placing, accuracy of strike-off, and the precision of the weighing scale.

(b) The weight of materials used per batch of concrete. The accuracy of these weights is dependent on the type and accuracy of batching equipment used.

(c) Specific Gravities of cement and aggregate.

(d) Absorption of water by aggregate in concrete.

(e) Moisture content of aggregate used in concrete.

The gravimetric method is not as accurate, rapid or practical as desired for field determinations of air content and requires a weighing scale which is difficult to transport and maintain under job conditions.



In both field and laboratory the accuracy of results depends on computations which must be carried to at least the fourth decimal place -- well beyond the accuracy obtainable with a slide rule.

The direct volumetric method (A.S.T.M. - C173 - 42T) is a widely used laboratory method. In this method the absolute volume of a known weight of concrete is obtained by displacing the air in the concrete with water. The air content is then obtained by subtracting the absolute volume from the bulk volume of an equal weight of the concrete. This type of test has several sources of error.

(a) In the displacement process, the sample of concrete is diluted with some six to eight times as much water as the original sample contained. This further solution of the cement particles causes shrinkage which will be greater than that in the original mix. As a result the percentage of air as determined is too high.

(b) Another source is the possibility of not displacing all the air from the sample in the washing-out process.

(c) The difficulty encountered due to foam and scum from the air-entraining agent in bringing the final volume of water up to the pycnometer calibration level.

(d) Weight per cubic foot of concrete. This measurement is dependent on the accuracy of the sampling, uniformity of placing, accuracy of strike-off, and the precision of the weighing scale.

(e) A temperature correction is required to get the accurate volume of water displacing the air. This requires calculations accurate to four significant figures.

The volumetric method is not practical for field determinations of air content as it requires scales accurate to .5 grams in the field. The method is very time-consuming as well as requiring calculations of



accuracy considerably beyond that of the slide rule.

Two new methods of measuring the air content of fresh concrete have been advanced in the last few years. A vacuum method has been advocated. This method consists essentially of measuring the amount of water required to replace the air removed from a given volume of concrete during agitation under a reduced pressure. This method effects a more complete removal of the air, especially from concretes containing air entraining agents. However, this method is practically restricted to laboratory testing because of the numerous weighings and measurements involved. Considerable trouble is encountered with the foam resulting from the use of air-entraining agents. It is sucked off during the de-airing process but cannot be discarded because of its water content. It is drawn off into a trap where further suction breaks it down so that it can be taken into account in the calculations.

The pressure method<sup>1</sup> in which the concrete is placed in a closed, pressure-tight vessel and then subjected to pressure to compress the entrained air, is the method used in this investigation. By the application of Boyle's Law, according to which the volume of a gas (at a given temperature) is inversely proportional to the pressure to which it is subjected, the volume of air present in the concrete is determined by the amount it is compressed by a given increase in pressure.

This method is well adapted for field testing as the pressure meter can be calibrated to indicate directly the gross air content of fresh concrete. As a result it was decided to design a pressure air meter which would be well suited for rapid and accurate air-content determinations both in the laboratory and the field.

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<sup>1</sup> Journal of the American Concrete Institute, Vol. 17, June 1946, p. 657.  
- A Method for Direct Measurement of Entrained Air in Concrete, by  
W.H. Klein and Stanton Walker.



### General Details of Design and Description of Meter

It was decided to keep the design as simple as possible by using standard pipe sizes and fittings wherever possible. This kept the machining costs at a minimum and made the pressure meter as economical a unit as possible.

In deciding on the size of the meter container two things had to be kept in mind. First of all the meter as a unit had to be of such a size, shape, and weight as to be readily handled by one man. Secondly, the container and stand pipe had to be of such a size as to ensure volume changes that could give scale divisions of 0.1 percent. A container of 0.3 cubic foot volume was considered the upper limit for handling by one man. Volume changes of one percent in the container give water level changes of one inch in a  $1\frac{1}{2}$ -inch diameter stand pipe. This allowed a calibration accuracy of around 0.05 percent which is adequate. A 10-inch length of 8-inch diameter wrought iron pipe was used for the container. A standard water gauge was used for the scale. The meter scale was calibrated for an applied load of 15 p.s.i. An ordinary bicycle pump is adequate for applying this pressure. The pressure gauge used on the meter has a working pressure of 30 p.s.i. with scale divisions to the nearest pound. A rubber gasket is used to make the junction between the container and the stand pipe air and water tight. (See Figure 1).

### Calibration of Air Meter

The calibration of the air meter was carried out in the manner suggested by "Klein and Walker"<sup>2</sup>. The calculation of the air content is based on Boyle's Law -- the volume occupied by a given mass of any gas at constant temperature varies inversely as the absolute pressure to which

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<sup>2</sup> Journal of the American Concrete Institute, Vol. 17, June 1946.  
A Method for Direct Measurement of Entrained Air in Concrete by  
W.H. Klein and Stanton Walker.



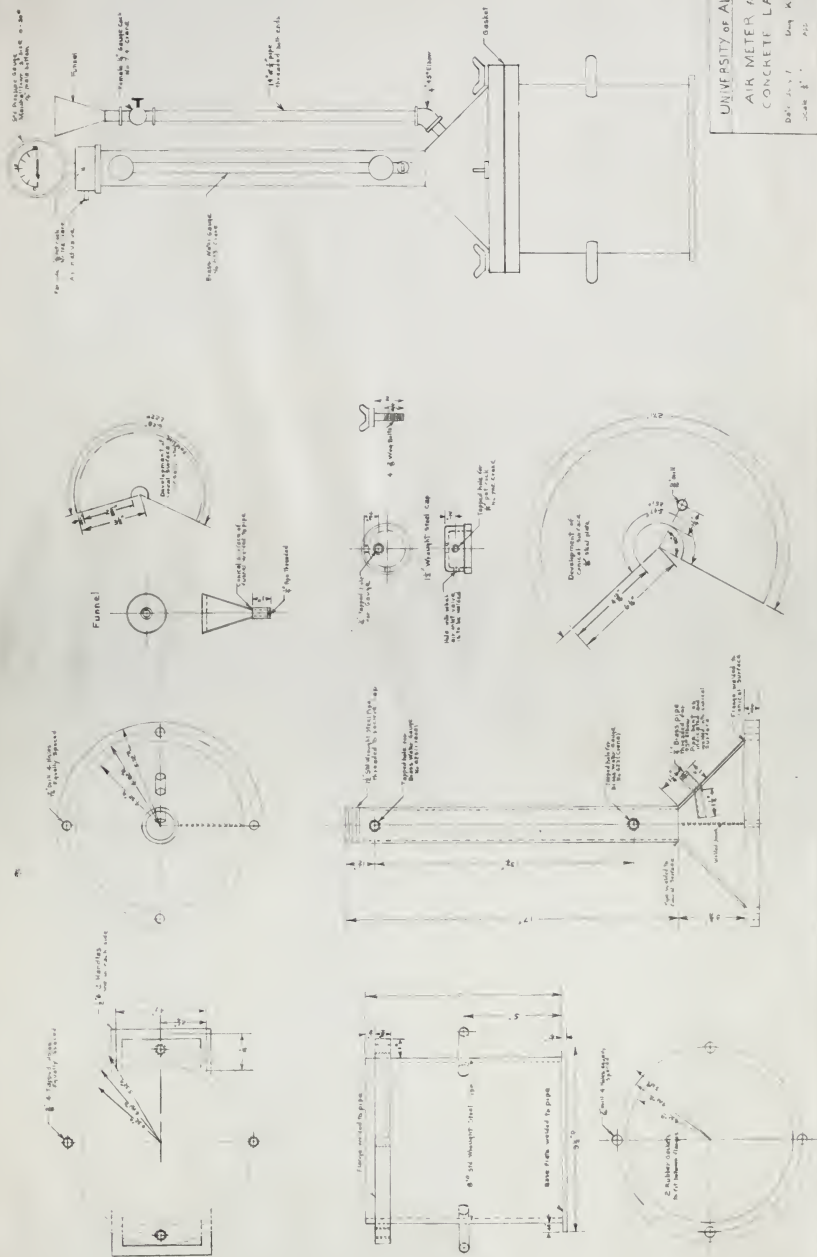


Figure 1. Detail Drawings of Pressure Air Meter



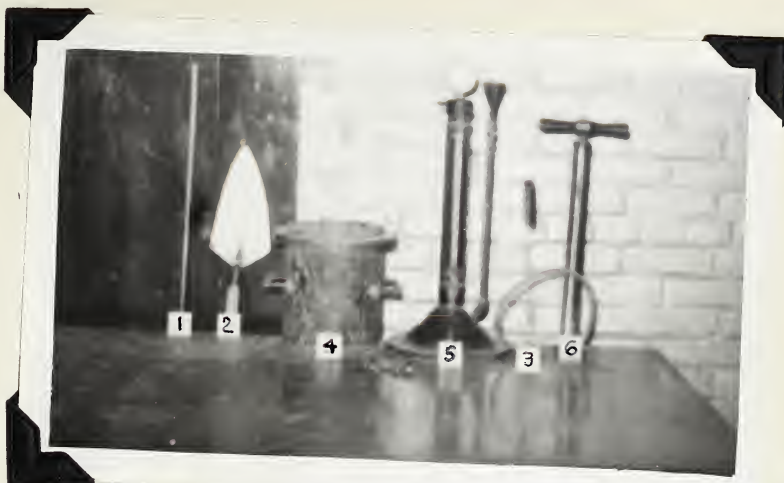


Figure 2. Unassembled Air Meter and Accessories  
1. Tamping rod 2. Trowel  
3. Brush 4. Meter Container  
5. Meter stand pipe and cone. 6. Air Pump



Figure 3  
Assembled Air Meter



it is subjected.

$$\frac{V}{V - r} = \frac{P_2}{P_1} \quad (1)$$

where V = Volume of air in concrete

r = reduction in volume due to pressure

P<sub>1</sub> = Initial absolute pressure

P<sub>2</sub> = Final absolute pressure

The initial pressure consists of barometric pressure, the pressure due to the concrete in the container and the water in the stand pipe.

The final pressure consists of the gauge pressure plus the initial pressure minus the change in height of water column in the stand pipe due to applied gauge pressure.

V<sub>1</sub> = Volume of air in fresh concrete in container

V<sub>2</sub> = Volume of air in fresh concrete in container after water has been brought to zero mark in cone assembly.

V<sub>3</sub> = Volume of air in fresh concrete in container after application of pressure.

V<sub>4</sub> = Volume of container

h<sub>1</sub> = Average pressure exerted by concrete (taken as head of concrete to mid-height of measure)

h<sub>2</sub> = Pressure exerted by volumn of water brought to mark in cone assembly

h<sub>3</sub> = Pressure exerted by column of water in cone after application of pressure.

B = Barometric pressure.

P = Gauge reading on application of pressure.

R = Reduction in volume of water in calibrated tube and stand pipe on application of pressure P.



Then

$$\frac{V_1}{V_2} = \frac{B + h_1 + h_2}{B + h_1} \quad (2)$$

$$\frac{V_2}{V_3} = \frac{P + B + h_1 + h_3}{B + h_1 + h_2} \quad (3)$$

$$V_3 = V_2 - R \quad (4)$$

Combining equations 2, 3 and 4

$$V_1 = \frac{R (B + h_1 + h_2) (P + B + h_1 + h_3)}{(B + h_1) (P - h_2 + h_3)} \quad (5)$$

The percentage of air "A"

$$A = 100 \frac{V_1}{V_4} \quad (6)$$

Combining equations 5 and 6

$$R = \frac{A V_4}{100} \frac{(B + h_1) (P - h_2 + h_3)}{(B + h_1 + h_2) (P + B + h_1 + h_3)}$$

The following calculations are made for an indicated air content of 8%.

$$R = \frac{A V_4}{100} \frac{(B + h_1) (P - h_2 + h_3)}{(B + h_1 + h_2) (P + B + h_1 + h_3)}$$

$$A = 8$$

$$V_4 = 0.29 \text{ (calibrated volume of container)} = \overset{501.1}{(0.501)} \text{ cubic inches}$$

$$B = 13.60 \text{ (average barometer pressure for Edmonton area)}$$

$$h_1 = \frac{5 \times 145}{12 \times 144} = 0.42 \text{ p.s.i. (pressure due to weight of concrete in container)}$$

$$16.9'' \quad h_2 = 0.61 \text{ p.s.i. (pressure due to column of water in stand pipe at zero calibration mark)}$$

$$h_3 = 0.33 \text{ p.s.i. (pressure due to column of water in stand pipe at 8% calibration mark)}$$

$$P = 15 \text{ p.s.i. (working pressure of air meter)}$$

$$1 \text{ psi} = 2.31 \text{ ft. water}$$

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$$R = \frac{8 \times 501}{100} \frac{(13.60 + 0.42)(15 - 0.61 + 0.33)}{(13.60 + 0.42 + 0.61)(15 + 13.60 + 0.42 + 0.33)}$$

14.72

$$= 19.3 \text{ cubic inches}$$

29.35

Area of stand pipe = 2.04 square inches

Area of water gauge tube = 0.20 square inches

Reduction in water column length for 8% air under 15 p.s.i. applied pressure

$$= L = \frac{19.3}{2.24} = 8.63 \text{ inches.}$$

In a like manner the reductions in water column length for various other air contents were obtained, thus giving a calibrated scale reading in gross air content of the fresh concrete in the container.



TABLE I  
AIR METER CALIBRATION TABLE

A %	R (cu.in.)	L (inches)
1	2.41	1.08
2	4.84	2.16
3	7.24	3.24
4	9.68	4.33
5	12.07	5.40
6	14.46	6.48
7	16.88	7.55
8	19.30	8.63
9	21.72	9.71

Procedure in Determining Air-Content by the Pressure Method

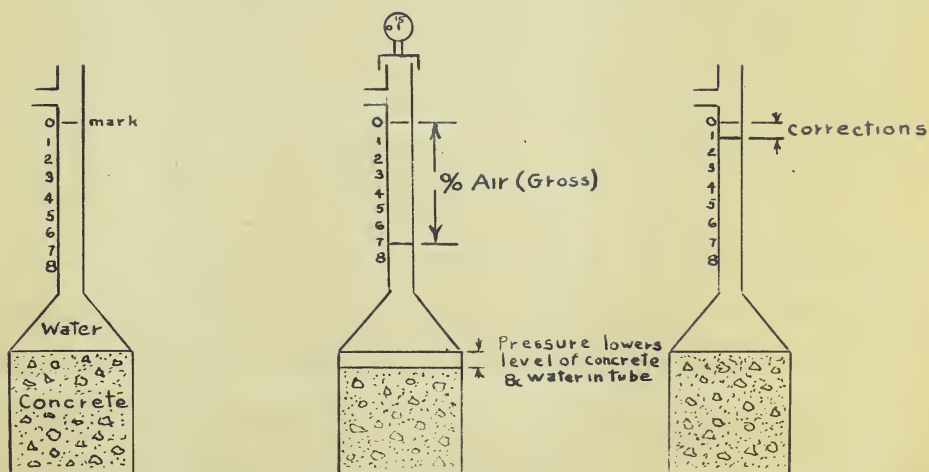


Figure 4. Illustration of Pressure Method of Test for Air Content



A 0.30 cubic foot sample of concrete is placed in the container of the pressure meter. The container is filled in three lifts of equal volume, each lift being rodded twenty-five times. On completion of rodding each lift, the container is struck sharply ten times with the tamping rod. This will bring the mortar to the surface and thus prevent excessive quantities of air being trapped by the following lift. A sheet of plexiglass was found to be very satisfactory for leveling off the concrete in the container and for finishing the concrete surface. However, a trowel or the tamping rod would be adequate in the field. The cone shaped cover is then clamped to the flange of the container, a pressure tight seal being obtained with a thin rubber gasket. Pressure is then applied to the surface of the concrete through the water in the stand pipe which is attached to the vertex of the cone. The air pressure is furnished by a small bicycle pump, and is measured by the pressure gauge on top of the stand pipe. The contraction in volume of the air in the concrete with the increase in pressure is indicated by a lowering in level of the water in the glass gauge connected to the stand pipe. The scale on the glass gauge is calibrated to indicate the total air content directly for an applied pressure of 15 p.s.i. The applied air pressure is then released slowly allowing the water column to come back to rest near zero. This difference from zero has to be noted and subtracted from the total reading.

The variation of barometric pressure in any one general locality is not likely to be sufficient to cause appreciable error in the meter calibration. However, barometric pressures do vary sufficiently from locality to locality. This variation can be taken into account without appreciable error by changing the applied pressure.



### Corrections Made to Gross Air Content Reading

The actual air content (net air content) of the concrete is obtained by subtracting a correction factor from the total (gross) air content reading. This factor corrects for:

1. Compression of the air in the aggregates.

This factor is determined independently by applying pressure to a sample of fine and coarse aggregate in the same condition, amount, and proportions as they occur in the concrete sample under test. It is generally more convenient to determine this factor on separate samples of fine and coarse aggregate. In running this test the aggregate should be poured slowly into the container filled with water. Vigorous stirring should accompany the pouring in an effort to keep the air trapped about the aggregate particles to a minimum.

The air content of the aggregate depends upon the absorption and moisture content of the aggregate.

TABLE 2  
AIR CONTENTS OF AGGREGATES

Type of Aggregate	Condition of Aggregate	% Air Content
Sand	Natural saturated state	0%
	Oven dried and resoaked	0.1% to 0.2%
	Oven dried	0.3% to 0.4%
Gravel	Natural saturated state	0%
	Oven dried and resoaked	0% to 0.3%
	Oven dried	0.3% to 0.6%

The above results can be verified by calculation on knowing the absorption and moisture content of the aggregate and the proportions used in the particular mix.



This compression factor for the aggregate used need only be checked when the source of aggregate is changed or there is a marked change in the absorption of the aggregate.

## 2. Expansion of apparatus under applied pressure.

This expansion is measured by noting the drop in level of the water in the graduated gauge tube when the apparatus filled only with water is subjected to the same pressure as is applied in the test of a sample of concrete. The expansion factor for the meter used in the laboratory is 0.1 percent.

## 3. Recovery factor.

On release of the applied pressure the water column does not as a rule return to the zero mark. This is due to a readjustment of the concrete mass under the applied pressure and cannot be attributed to the air content of the concrete. The percentage that the water column does not recover on release of the applied pressure has to be subtracted from the gross air content reading. This percentage is called the recovery factor.

In laboratory work the above three correction factors should be subtracted from the total air content reading to get the net air content of the concrete. When used as a control in field testing sufficient accuracy is obtained by correcting for the recovery factor.

## Comparison of Air Content Determination Methods

Results used are from tests made in the laboratory. Local sands and gravel were used in all cases. Some of the batches of concrete were made without air entraining agents, while in the majority of cases air was entrained by the use of commercial air-entraining agents. A few tests were carried out using air-entraining portland cement. All batches were mixed in the 0.5 cubic foot laboratory mixer.

The diagrams of Figures 5, 6 and 7 compare air contents as determined by the gravimetric, volumetric, and pressure methods.



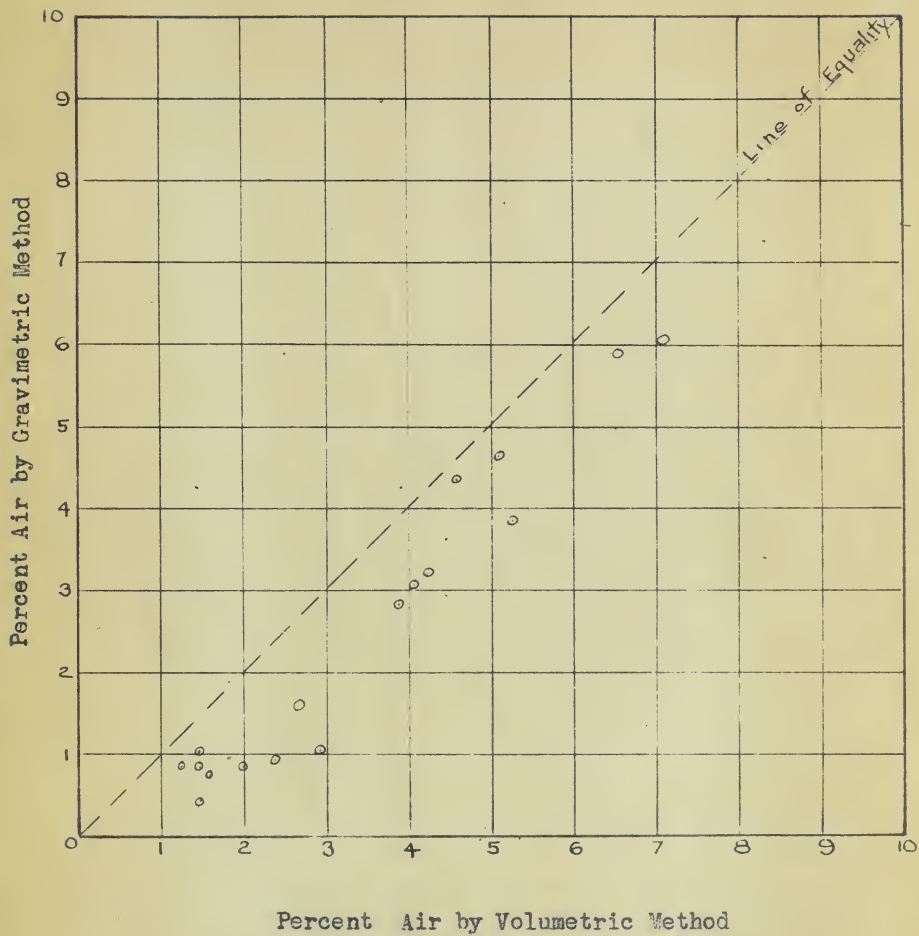


Figure 5. Comparison of Air Contents by Gravimetric Method and by Volumetric Method.



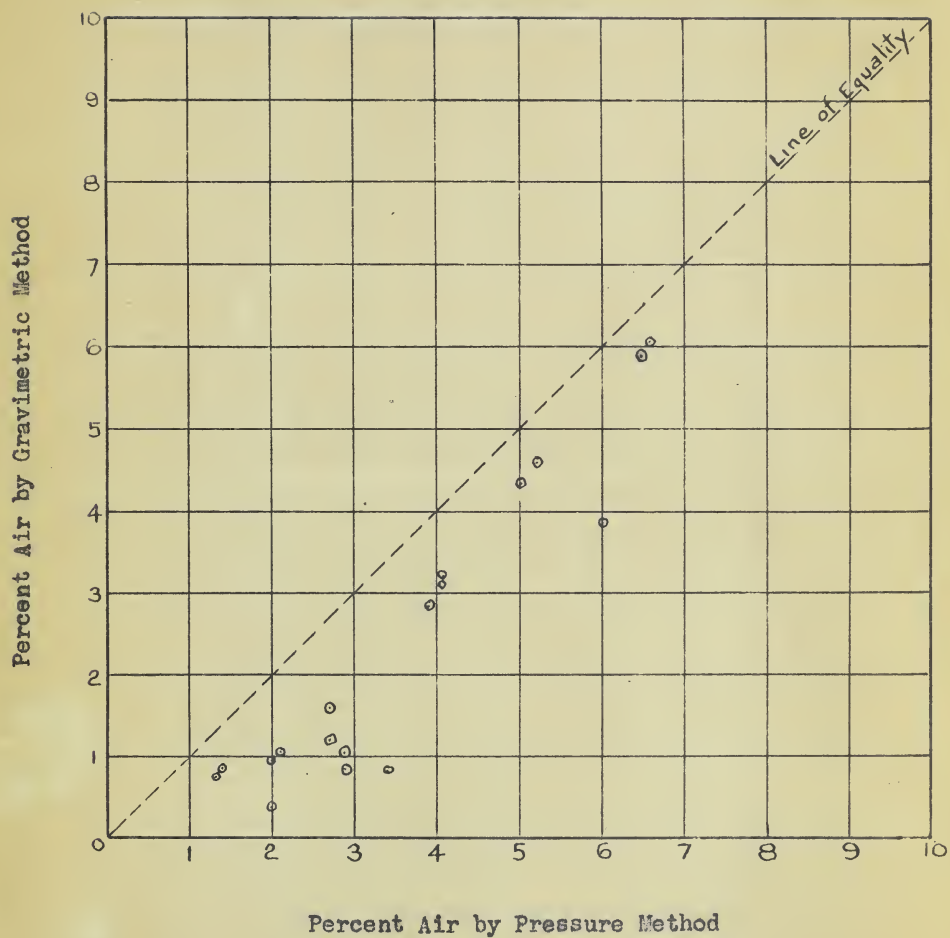


Figure 6. Comparison of Air Content by Gravimetric Method and by Pressure Method.



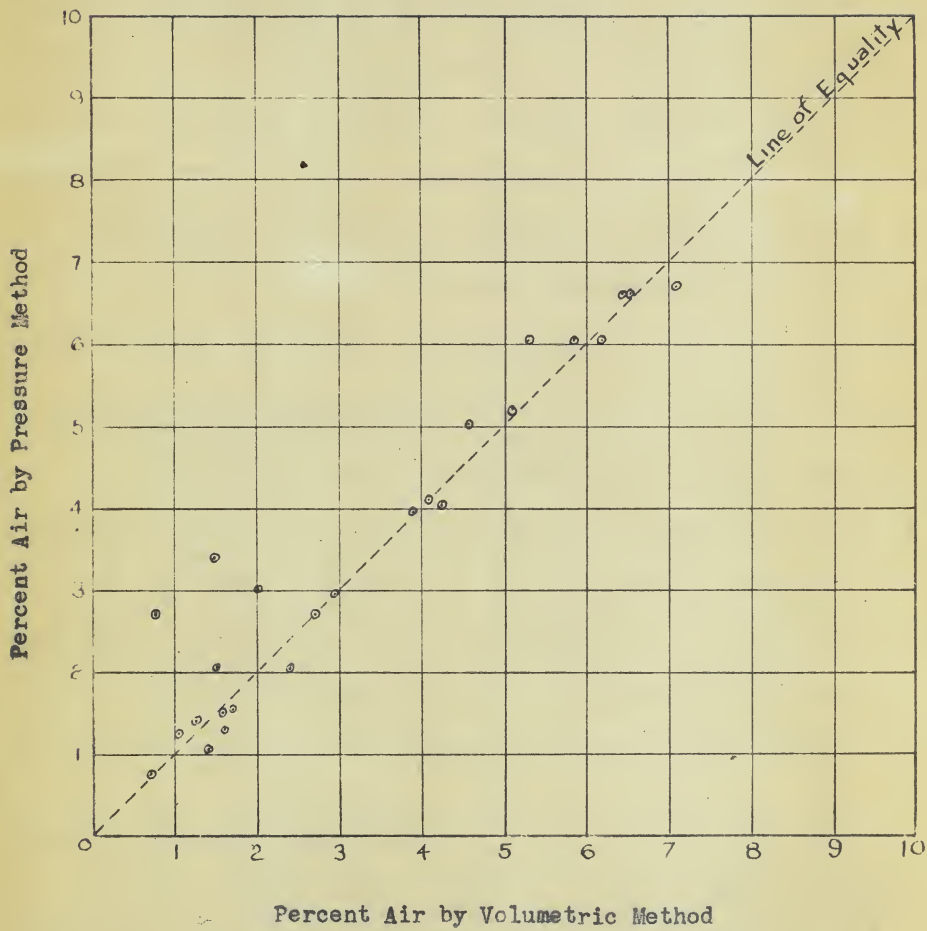


Figure 7. Comparison of Air Content by Pressure Method and by Volumetric Method.



### Gravimetric vs. Volumetric

The best fit line of the plot of % Air Content (gravimetric method) vs. % Air Content (volumetric method) is parallel but displaced considerably to the right of the line of equality. The graph indicates the the gravimetric method gives air contents some one percent lower than the volumetric method. This difference is consistant with those found by others between the gravimetric and volumetric method. J.C. Pearson<sup>3</sup> reported an average difference between the two methods of 0.8 percent. In several of the tests when no air entraining agent was used the gravimetric method was found to indicate negative air contents. This is probably due to the inaccuracy of obtaining the weight per cubic foot of the concrete, which is dependent on the accuracy of sampling, uniformity of placing, and accuracy of the strike-off.

### Gravimetric vs. Pressure Method

The best fit line of the plot of % Air Content (gravimetric method) vs. % Air Content (pressure method) is offset to the right of the "line of equality". The two lines are not parallel indicating that the gravimetric method gives results closer to those of the pressure method at the higher air contents. In general the gravimetric method indicates air contents some one percent lower than the pressure method.

### Volumetric vs. Pressure Method

The best fit line of the plot of % Air Content (volumetric method) vs. % Air Content (pressure method) nearly coincides with the line of equality. There is a very good check between the two methods. The graph does indicate that the volumetric method tends to give slightly

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<sup>3</sup> Proceedings of the American Society of Testing Materials, 1944 -  
Volumetric Method of Determining the Air Content of Freshly Mixed Concrete.



higher results at lower air contents and slightly lower results than the pressure method at high air contents.

### Conclusions

A very good check was obtained between the results from the pressure method and the volumetric method. The pressure method has, however, the advantage of being much more rapid and requires no computing. This makes it an ideal method for field testing.



## CHAPTER II

SONIC EQUIPMENTIntroduction

Two important dynamical properties of any elastic system are the natural frequency of vibration and damping capacity. In the case of a vibrating beam of given dimensions, the natural frequency of vibration is related principally to its modulus of elasticity and the mass density.

The modulus of elasticity of materials such as concrete has been determined during the past few years by dynamic methods. This method requires the measurement of the natural frequency of vibration of prismatic bars, from which the modulus of elasticity can be calculated by various known relations, depending on the nature of the vibrating system employed. Both longitudinal and flexural vibrations have been used, the specimen being vibrated by electro magnetic, electrostatic, or by mechanical means.

Equations Used

In any complete text book on sound there may be found the following equation relating the natural frequency of vibration of a beam to the modulus of elasticity.

$$f = \frac{k V m^2}{2 \pi l^2} \quad (1)$$

$$V = \sqrt{\frac{E}{\rho}} \quad (2)$$

where  $E$  = modulus of elasticity

$V$  = velocity of sound

$\rho$  = density

$l$  = length of specimen

$f$  = resonant frequency in kilocycles

$k$  = radius of gyration of the section about an axis perpendicular to the plane of bending  
( $k = \frac{t}{\sqrt{12}}$  for rectangular cross section).



$t$  = thickness of beam

$m$  = number depending on mode of vibrating beam  
and on ratio  $\frac{d}{L}$

= 4.73 for fundamental and small ratios of  $\frac{d}{L}$

By eliminating  $V$  from equations (1) and (2) and solving for

$E$  we get

$$E = \frac{4\pi^2 l^4 f^2 Q}{k^2 m^4} \quad (3)$$

Equation (1) was obtained by solving the differential equation for the motion of a bar vibrating in flexure in the free mode. When a bar vibrates a cross-sectional element may be thought of executing two movements, a motion of translation laterally, and one of rotation relative to the position of the unbent neutral axis. In the derivation of equation (3), the rotary inertia was neglected for the sake of simplicity and because in most cases the error introduced thereby is not large. However, if the thickness of the vibrating beam is relatively large compared to the length, as in the case in most concrete beams, the rotatory inertia must be taken into account. Also neglected are the effects of the moments of shear and lateral inertia. Lateral inertia is due to the lateral contraction and expansion of the vibrating bar. A more rigorous solution has been worked out in which these effects are taken into account.

The results of this solution give:

$$E = \frac{4\pi^2 l^4 f^2 Q}{k^2 m^4} T$$

where  $T$  is a complicated correction term depending on the ratio of thickness to length and on Poisson's ratio. The values of  $T$  for different ratios of thickness to length are shown in Figure 8. This correction is applicable to beams of rectangular cross-section only.



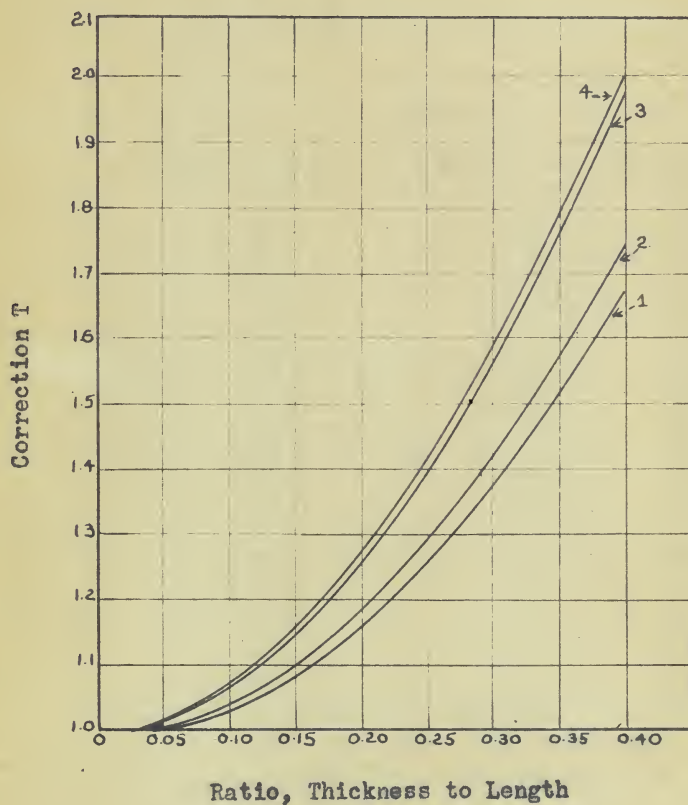


Figure 8. Correction Term T

- Curve 1 - Correction curve for rotary inertia
- Curve 2 - Correction curve for rotary and lateral inertia -  
Poisson's ratio = 0.11
- Curve 3 - Correction Curve for rotary inertia and shear -  
Poisson's ratio = 0.11
- Curve 4 - Correction curve for rotary inertia and shear -  
Poisson's ratio = 0.16



To obtain the corresponding correction curve for a circular beam it is only necessary to multiply the scale of the abscissas by  $\frac{2}{\sqrt{3}}$ , the ratio of the radius of gyration of a rectangular beam to the radius of gyration of a circular beam.

The correction factor  $T$ , may also be obtained from the following table:

TABLE 3

CORRECTION FACTOR  $T$  FOR MODULUS OF ELASTICITY

$K/L$	$T$	$K/L$	$T$
0.00	1.00	0.09	1.60
0.01	1.01	0.10	1.73
0.02	1.03	0.12	2.03
0.03	1.07	0.14	2.36
0.04	1.13	0.16	2.73
0.05	1.20	0.18	3.14
0.06	1.28	0.20	3.58
0.07	1.38	0.25	4.78
0.08	1.48	0.30	6.07

where  $K$  equals the radius of gyration - for a cylinder

$$K = d/4, \text{ for a prism } K = \frac{t}{2\sqrt{3}}$$

$L$  = length of specimen

These values of  $T$  are for Poisson's ratio of  $1/6$ .



## Apparatus

The dynamic testing apparatus consists of a method of supporting the specimen so that it will vibrate in some prescribed mode of vibration; second, a method of vibrating the specimen in that mode; third, a means of measuring the frequency of vibration; and fourth, a measurement of the dimensions and density of the specimen.

The means of support should permit the specimen to vibrate transversely in the free mode without restriction. This was accomplished by supporting the beam at its nodal points (0.224 of its length from each end) or on a thick pad of sponge rubber. Identical results were obtained also by supporting the beam at its ends. Supporting the beam at its ends would not prove feasible as disintegration progressed under freezing and thawing. Supporting the beam at its nodal points was found to give better and more consistent results than those obtained with the beam supported on the rubber pad. This is quite possibly due to the fact that the beams are tested in the saturated condition so that an adhesive or suction force is developed between the beam and rubber pad causing a damping effect on the vibration. This damping effect was found to cause differences of as much as 100 cycles/sec. in the resonant frequencies. As a result it was decided to vibrate the beam with supports at the nodal points. The supports used were obtained by splitting a 1/8" square steel bar down a diagonal.

The driving circuit consists of a variable frequency audio oscillator, and a driving unit. The oscillator is a Hewlett Packard No. 11012, calibrated to read within  $\pm 2\%$  of the true frequency over its range of use (550 to 6000 cycles). The oscillator is coupled through a transformer to a 6 inch magnet type loud speaker, a light aluminum rod being cemented to the voice coil of the speaker, for transmitting the



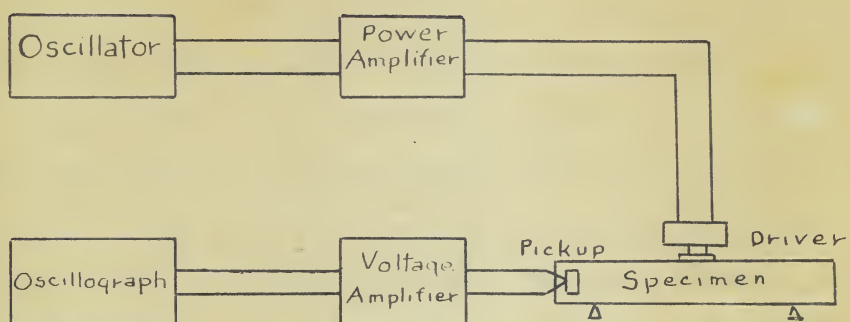


Figure 9. Schematic Diagram of Sonic Equipment

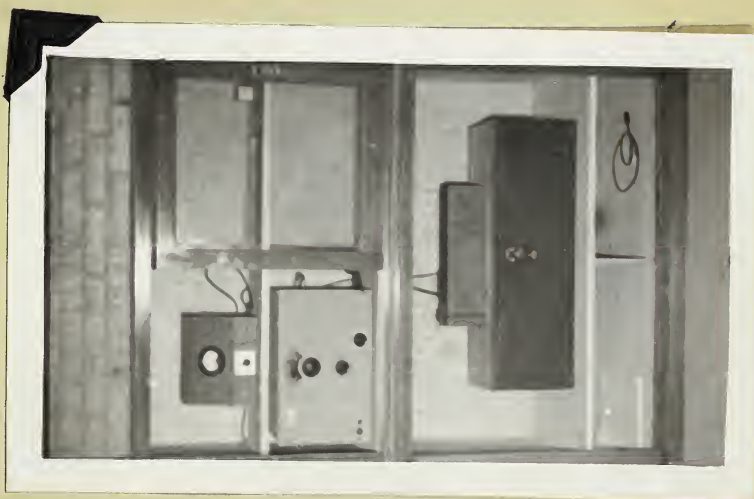


Figure 10. Sonic Equipment



vibration to the specimen. The speaker is attached to a wall of the beam supporting box by a hinge in such a way that the driving rod protrudes through a hole in the top and can be brought into contact with the underside of the supported beam by means of an adjusting screw. The speaker was found to have a resonant frequency of its own at around 650 cycles/sec. This is well below the resonant frequency of most concrete specimens tested and should not give testing difficulties.

The pickup circuit consists of a pickup unit, an amplifier, and a meter. The pickup unit should be of the type which generates a voltage proportional to the amplitude or velocity of vibration of the test specimen. It is required that the vibrating parts of the pickup be small in mass as compared with that of the test specimen. This is to guard against the pickup having a resonant frequency within the range of the test specimen. A piezo-electric crystal pickup was tried first. It proved unusable because of the inconsistent and erratic results obtained with it. Much of the trouble was probably due to the needle contact which proved over-sensitive. The crystal pickup was also found to have a series of resonant frequencies from 500 to 1000 cycles/sec. An electro-magnetic pickup proved satisfactory giving consistent results. This type of pickup has a much larger contact surface and as a result is not as susceptible to local aggregate vibrations as the crystal pickup. This type of pickup was also found to have a flat resonant peak at around 700 cycles/sec. This type of resonant peak will not give testing difficulties. Due to the low impedance of electro magnetic pickup less difficulty can be expected from stray electrical disturbances. Since the ratio of the amplitude at the ends to that at the center of a beam vibrating in the free free mode is approximately 1.6, better results are obtained by placing the pickup in contact with the end of the beam.



Since many specimens will vibrate at their natural frequency when excited at half or one third, or even one fourth their natural frequency, care must be taken that the oscillator and specimen are vibrating at the same frequency. This is readily ascertained by synchronizing the sweep frequency of an oscillograph with the oscillator frequency and by placing the pickup unit first on the speaker and then on the specimen; an identical frequency is shown if the same number of waves appear on the oscillograph for each case. By using a double switch the oscillator and pickup can be both connected to the oscillograph and a comparison of waves can be more readily made. Familiarity with the relationship existing between beam size, concrete strength, and resonant frequency make the use of an oscillograph unnecessary.

The dimensions of the specimen should be determined with considerable accuracy ( $\pm 1\%$ ) because they are used to a power in the equation relating resonant frequency and the modulus of elasticity. The density of the specimen is best obtained by obtaining the weight of the beam while submerged. This proved more accurate than weighing the displaced water because of the varying effect surface tension had on the amount of water displaced. The density of the beam is best obtained while in the original state before undergoing freezing and thawing. This density can be used in all subsequent calculations as the cycles of freezing and thawing have little or no effect on the beam's density.

#### Testing Procedure

The specimen is supported at the nodes. The driver is then brought into contact with the beam. The pickup is held in place on one end of the beam by a strong rubber band. The pickup should be placed on the top surface of the beam so that it will be actuated in the plane of



vibration. The frequency of the oscillator is then varied until the amplitude of vibration of the specimen reaches a maximum as shown by the meter. The reading on the frequency dial of the oscillator is then noted. The amplifiers in the driving and pickup circuits should be adjusted to provide a satisfactory meter reading. To avoid chattering of the driver against the specimen, the driving force should be maintained as low as is feasible for good resonance response.

### Conclusions

1. When the elastic behavior of concrete is studied under the action of a deteriorating agent it is often sufficient to present the results in terms of the frequency of vibration. If the results are to be compared with the findings of other investigators it is desirable to present them in terms of the modulus of elasticity which is a physical property of the material.

2. If quantitative values of the modulus of elasticity are to be determined it is necessary to correct the value for the size and shape of the specimen. This is done by using the correction curve of Figure 8.

3. Testing of the beams in a saturated condition proved satisfactory. Moisture changes were found to have an effect on the resonant frequency. However, they are negligible for any change which is apt to occur in normal practise.



## CHAPTER III

AUTOMATIC ACCELERATED FREEZING-and-THAWING APPARATUS FOR CONCRETEIntroduction

The resistance of concrete to frost action is dependent on many variables potentially present in the composition of the hardened material and the method of test. Such factors as the chemistry of the cement, degree and rate of hydration; the nature, grading, and thermal properties of the fine and coarse aggregate; and the homogeneity of the mixture affect the composition of the hardened concrete. The rate of cooling, degree of cooling, the rate of warming, degree of warming, size and shape of specimen, the relative degree of moisture saturation of the aggregate and matrix are independent variables which affect the resistance of the concrete to frost action.

It is impossible to reproduce in the laboratory conditions of weathering to which any particular member of a structure will be exposed. In one case a structure may be subjected to many and frequent reversals of freezing and thawing due to exposure to sunlight in the daytime and temperatures below freezing at night. In other cases a structure may be exposed for long intervals to very low temperatures. In most cases the structure would be under highly varying conditions of moisture saturation. The degree and depth of frost penetration of each cycle will be a function of the mass of concrete and the ambient temperature.

It is thus impossible to standardize a test procedure which will permit definite correlation with service of the structure. However, a procedure which is highly reproducible and sufficiently severe and rapid to permit determination of the potential relative durability of the concrete in question in sufficient time to make the data usable as the basis of an



acceptance test would be of great value. This type of procedure would be ideal for running comparative durability tests on concrete and concrete materials.

With this in mind, Charles E. Wuerpel and Herbert K. Cook<sup>4</sup>, devised an apparatus which "(a) would be entirely automatic and require no movement of the test specimens during the desired reversals of temperature, (b) would develop thermal gradients of a severe but highly reproducible nature, and (c) would maintain a constant moisture saturation influence. The premises upon which the mechanical design was based were: (a) reduction in specimen temperature from  $42 \pm 2^{\circ}$  F to  $0 \pm 2^{\circ}$  F in one hour; (b) elevation of the specimen temperature from  $0 \pm 2^{\circ}$  F to  $42 \pm 2^{\circ}$  F in the second hour, (c) repeated reversals of this cycle to the number desired, (d) immersion of the specimen at all times in the water, and (e) uniform thermal effects on all specimens tested."

A similar piece of equipment was designed, constructed and installed in the concrete laboratory. This unit has a capacity of 12 specimens as compared to the 102 specimens of Wuerpel's equipment.

#### Description of Apparatus

The apparatus consists essentially of three tanks; a specimen tank, cold tank, and thaw tank; with means for cooling the cold fluid, heating the thaw fluid, and circulating the cold and thaw fluids at the right temperatures in and out of the specimen tank during the right intervals of time. A schematic diagram of the apparatus is shown in Figure 11. The unit is capable of reducing the temperature of  $12 - 4\frac{1}{2} \times 3\frac{1}{2} \times 16$  specimens from  $55^{\circ}$  F to  $0^{\circ}$  F in one hour and in raising the temperature

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<sup>4</sup> Proceedings of American Society for Testing Materials, Vol. 45, 1945  
Automatic Accelerated Freezing-and-Thawing Apparatus for Concrete - p.813.



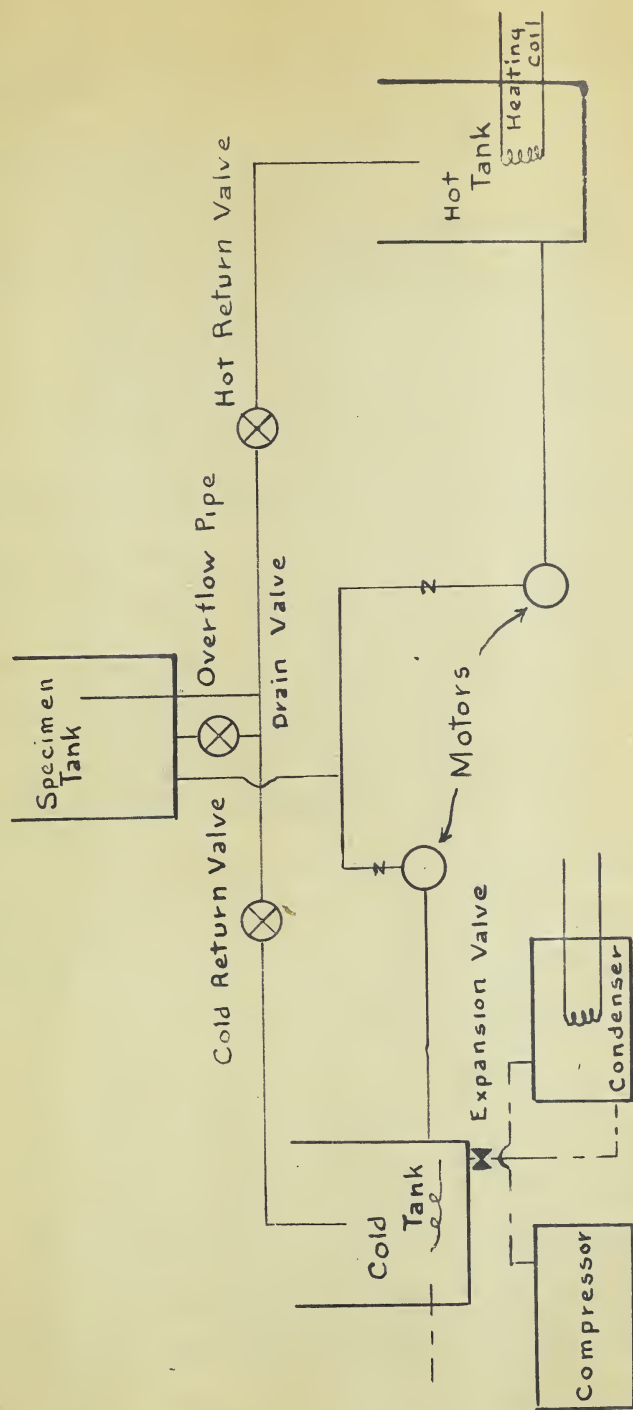


Figure 11. Schematic Diagram of Freeze-Thaw Apparatus



from 0° F to 55° F in the following hour. It will repeat the above 2 hour cycle any number of times. A detailed description of the units' various component parts follows.

#### Freezing-and-Thawing Solutions

A mixture of 60 percent denatured alcohol and 40 percent water is used for both the thaw and cold solutions. This mixture has a freezing point of -40° F. The cold fluid in the cold tank is kept at -20° F but the temperature of the cold plates of the refrigerator may be as low as -35° F making the alcohol water mixture necessary. The concentration of the mixture was not changed for the thaw fluid because of the intermingling of the fluids which is bound to occur and also because of the possible necessity of storing all the fluid in two tanks while the system undergoes repairs. Approximately 90 gallons of alcohol and 60 gallons of water were required to fill the system.

#### Cold Tank and Refrigeration Unit

The cold tank is made of 18 gauge galvanized iron with soldered joints. The inside dimensions are 24" x 24" x 48". The tank is insulated with 4 inches of cork. A vapour barrier of asphalt was placed between the tank and cork and between the cork and tongue and groove board sheathing. This vapor barrier prevents the formation of a layer of ice between the tank and cork insulation or insulation and sheathing. Four refrigeration plates in units of two, are supported 6 inches above the bottom of the tank. The plates are 19" x 21" x 1" having double radiation surfaces. The plates are controlled by a thermostatic expansion valve. The upper 8 inches of the tank house the expansion valves, refrigerant piping, and solinoid valve. The cold tank contains some 75 gallons of fluid when not in use. The cold fluid is removed from the bottom of the cold tank through





Cold Tank

Figure 12

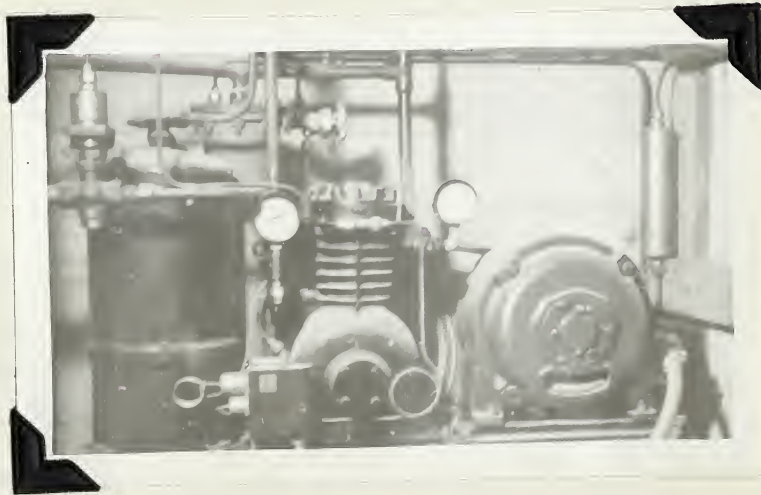


Figure 13  
Refrigeration Unit



a  $1\frac{1}{2}$ " pumpline. The fluid then passes through a strainer into the cold pump. It is then pumped passed a check valve and through a globe valve into the specimen tank. The globe valve is used to control the rate of flow of cold fluid into the specimen tank. A perforated pipe the length of the specimen tank distributes the cold fluid uniformly throughout the specimen tank. The cold fluid returns by means of a  $1\frac{1}{4}$ " gravity line from the overflow pipe.

This method of inlet and discharge provides ample circulation across the refrigeration plates and mechanical agitation is not required. The cold inlet and return lines are insulated with 2 inches of asbestos paste. An asphalt vapour barrier was placed on both sides of the insulation. The refrigeration is performed by a 2 H.P., 220 volt, 60 cycle, 3 phase, water-cooled condensing unit using Freon F-12 as the refrigerant. The unit has a capacity of 10,000 B.T.U. per hour.

#### Thaw Tank and Heating Equipment

The thaw tank is constructed out of 16 gauge galvanized iron with soldered joints. It is a circular tank 24" in diameter and 48 inches high. The thaw tank was not insulated as the thaw solution was to be kept at or near room temperature. The tank has a tongue and groove sheath cover which keeps evaporation losses to a minimum. Two 1000 watt, 200 volt immersion heaters are installed diagonally across from each other 6 inches above the bottom of the tank. The heaters are controlled by a thermostat set at 70° F which actuates a mercury switch which operates the heaters. The solution of the thaw tank is kept at a depth of 12 inches when the thaw fluid is in circulation. The thaw tank contains some 75 gallons of fluid when not in use. The arrangement and size of the circulation lines are similar to those for the cold fluid.





Figure 14

Thaw Tank

#### Specimen Tank, Racks, and Container

The specimen tank is constructed from 18 gauge galvanized iron with soldered joints. It has 2 inches of cork for insulation. A vapour barrier of asphalt was placed between the tank and cork and cork and tongue and groove sheathing. The cover consists of tongue and groove sheathing on both sides of a 2 inch layer of cork. The inside dimensions of the tank are 21" in depth, 21" in width, and 27 " in length. The tank is designed to hold 4 racks. Each rack is capable of holding 3 specimens. There is a  $1\frac{1}{4}$  inch diameter drain pipe in the bottom of the specimen tank. The flow through the drain is directed to the right tank by motorized valves. The overflow pipe consists of a horizontal  $1\frac{1}{4}$  inch diameter pipe with the upper half removed. It is connected to the vertical overflow drain line by a T fitting.



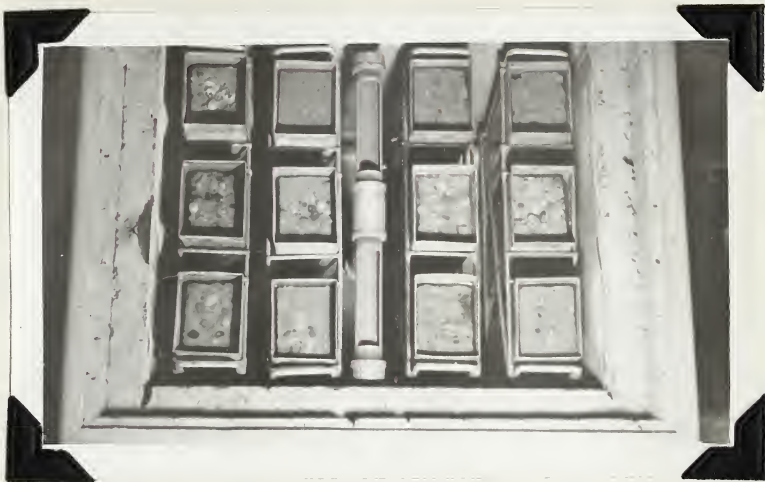


Figure 15. Plan View of Specimen Tank



Figure 16. Specimen Packs and Containers



The overflow pipe is centered in the tank and is as long as the specimen tank is wide. The solution is pumped into the specimen tank through two perforated pipes each running the length of the specimen tank. One is for the incoming thaw solution and one for the cold solution. The openings in these pipes are  $3/16$ " diameter at 6" centers. The openings are directed slightly downward from the horizontal so as to cause a circular flow of solution across the lower portion of the tank and specimens, up the other side, and back across the top portion to the overflow outlet.

The concrete specimens are placed in vertical containers made out of 18 gauge galvanized iron. The inside dimensions of these containers are  $3\ 3/4$ " x  $4\ 3/4$ " x  $17\ 3/4$ " deep.

The racks are made from  $1$ " x  $1$ " x  $\frac{1}{4}$ " angle iron and  $3/8$ " and  $\frac{1}{4}$ " rod. These rods form an open structure above the base made of the angle iron. This allows free circulation of the solution around the specimen containers. There are four racks identical in size each holding 3 specimens. The racks suspend the specimens 3 inches above the bottom of the specimen tank. The racks are of such a size as to be handled by one man.

#### Pumps, Valves, Controls, and Safety Device

The circulation of the cold and thaw fluids is accomplished by two centrifugal pumps rated at 25 U.S. gallons per minute at a 15 foot head. Direct connected motor pump units were used. Since only one solution is circulated at a time common pipes are employed in the overflow and drain lines from the specimen tank. The solution is directed to the proper tank by valving through three electrically operated globe valves. One on the cold return line, one on the thaw return line, and the other on the drain line. Since the specimen tank is at a higher elevation than the cold and thaw tanks, overflow and drainage from the specimen tank is accomplished by gravity flow through  $1\ 1/4$ " diameter pipes. All drainage lines and the cold pump line are insulated with asbestos paste. Leakage of solution from one tank to another through pump lines is prevented by a check





Figure 17. Automatic Valves

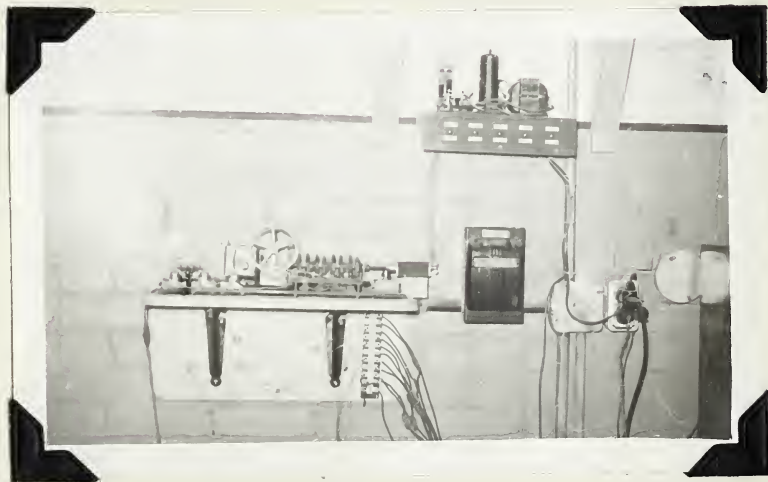


Figure 18. Automatic Timer and Safety Unit



valve installed above the pumps.

Since all valves and pumps are electrically operated, circulation of the solution is made entirely automatic by means of a 2 hour four circuit timer. The timer consists of a series of properly shaped cams mounted on a common shaft and driven by an electric motor. As the shaft revolves the cams will open and close the various circuits in their proper sequence. (See Figure 19 for circuit diagram). For example, consider the cold pump circuit. When the cam-operated contacts close the circuit is completed and the coil is energized and closes the relay starting the cold pump. When the contacts separate due to the rotation of the cam the circuit is broken, the relay opens and the pump stops. Similar circuits operate the hot pump and drain valves. However, the cold return valve and hot return valve are capable of being operated by a double relay since when one valve is closed the other valve can be opened in the same operation. This cuts down on the number of circuits required in the timer. The timer is fitted with a four circuit, double pole, double throw switch which when thrown to the right makes the controls automatic, and when thrown to the left makes manual control possible. An ordinary revolution counter which records the accumulative number of cycles is attached to the cam shaft. Figure 18 shows the timer, the counter, and liquid level safety controls. The sequence of operation of the valves and pumps is given below.



TABLE 4  
SEQUENCE OF OPERATION OF VALVE AND PUMPS

Elapsed Time			Operation
Hr.	Min.	Sec.	
0	0	0	Drain valve closes
0	0	30	Cold return valve opens
0	1	0	Cold pump starts
0	54	0	Cold pump stops
	54	2	Drain valve opens
1	0	0	Drain valve closes
1	0	30	Thaw return valve opens
1	1	0	Thaw pump starts
1	54		Thaw pump stops
1	54	2	Drain valve opens
2	0	0	Drain valve closes

Without automatic liquid level control devices it is possible for any of the three tanks to be filled to overflowing because of failure of any of the electric valves to operate. Because the cold return valve is at a lower elevation than the hot return valve there is a gradual transfer of solution to the cold tank. This requires a periodical re-transfer of solution from the cold tank to the thaw tank. Overflow and loss of solution by either of the above means is prevented by a pair of liquid level control probes installed in each tank just below the point where overflow might occur. See Figure 20 for circuit diagram of liquid level safety controls. When the liquid control probes are not shorted by touching the solution a voltage drop occurs across the 100K resistor. This voltage drop puts a potential on the probe in the cold cathode tube causing it to fire, and thus pass current through relay coil number one, and consequently closing relay switch number one. This completes the current through relay coil number two and keeps the contacts on relay number two closed. This in turn completes the circuit through the hold



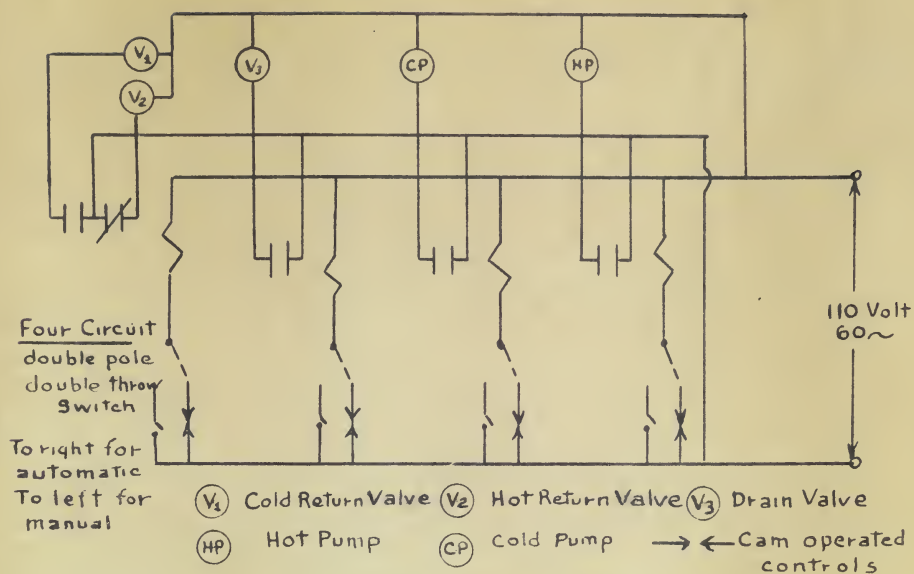


Figure 19. Automatic Timer for Freeze-Thaw Apparatus

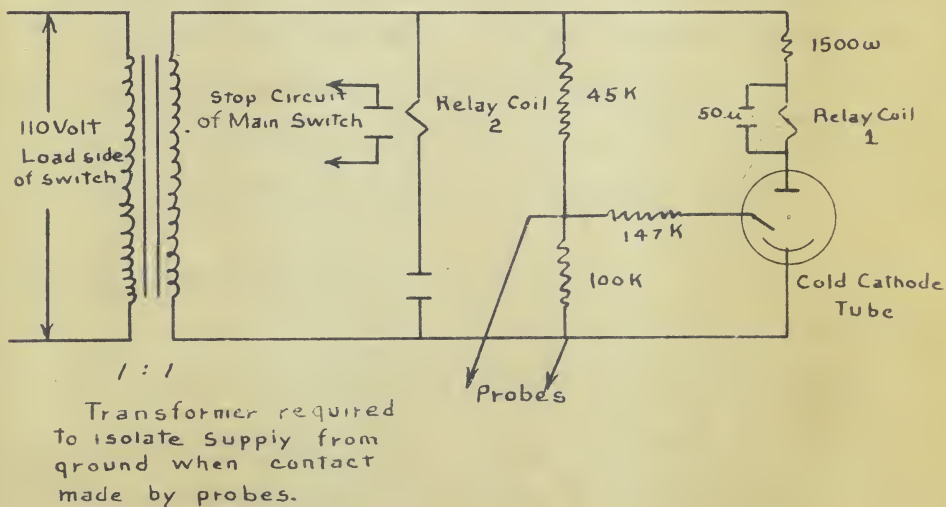


Figure 20. Liquid Level Safety Control Circuit



button for the supply for the whole unit. When the liquid control probes are shorted by coming in contact with the solution no potential is developed on the probe in the cold cathode tube. As a result the tube passes no current. This opens relay number one which breaks the circuit in relay coil number two. This in turn breaks the hold button circuit and cuts the whole unit from the supply. This maintains the solutions at whatever level they may be. The solutions can then be redistributed by use of the manual controls.

#### Temperature Records

A beam with thermo couples embedded in its ends was used to check the circulation of the fluid in the specimen tank and to determine its effect on beams in various positions of the tank. A thermo couple was also suspended in the center of the specimen tank to get the mean temperature of the circulating fluid during a freeze-thaw cycle. The normal operating temperature of the circulating fluid and the temperature changes of the thermo couple specimens are shown in Figure 21. The circulating fluid holds its temperature very well giving rapid freezing and thawing. The temperature difference between the top and bottom ends of the specimens will have little if any effect on the results especially if the specimens are turned end for end daily on completion of testing.

#### Operation of Equipment and Testing of Specimens

Except for routine checking of the liquid level in the hot and cold tanks and for general mechanical operation the unit is completely automatic. A great advantage of this type of unit is that the specimens require no handling except when actual testing is required. The unit does give a large number of exposure cycles rapidly and without attention.



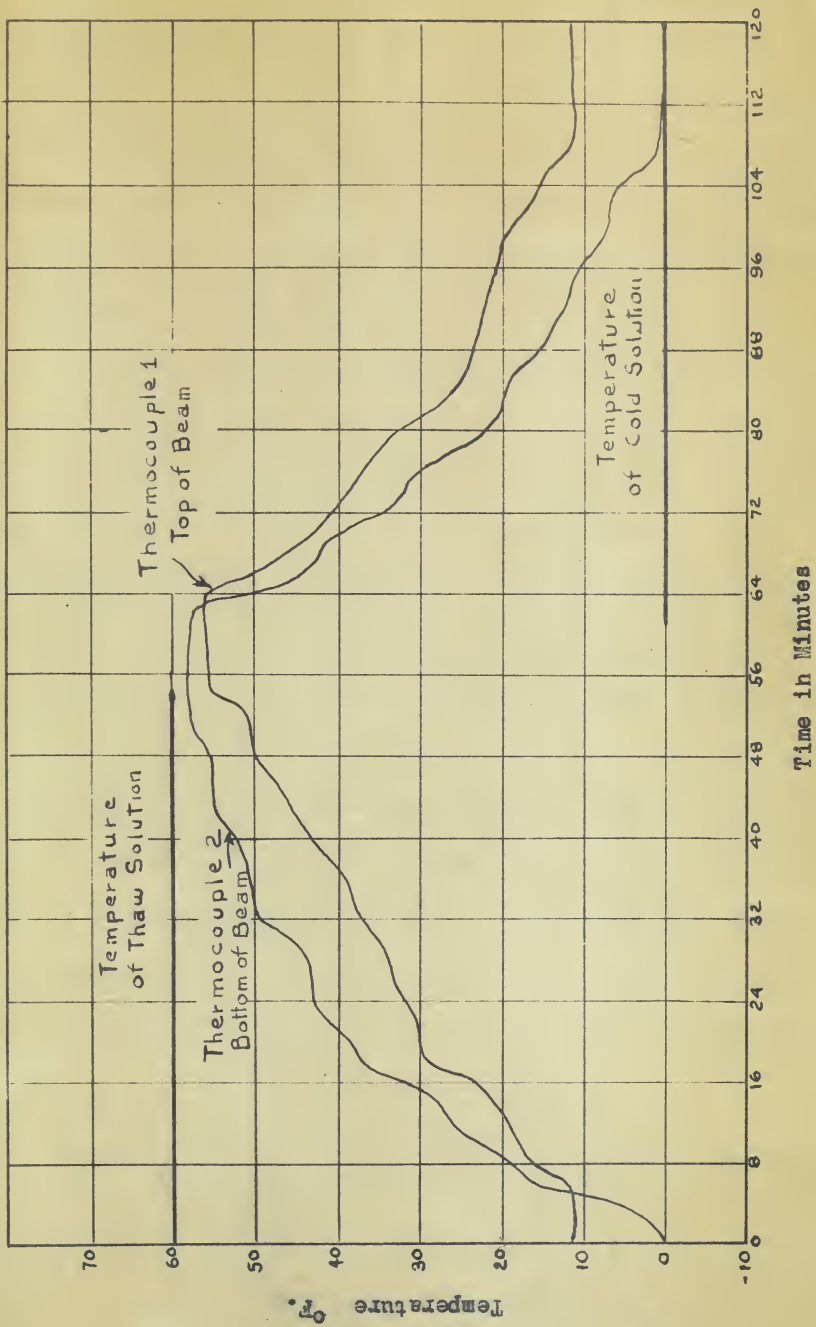


Figure 21. Typical Freeze-Thaw Cycle



A suggested laboratory procedure is to store the specimens in water at 70° F for nine days after making before subjecting them to the accelerated freezing and thawing test. This makes it possible to furnish test results by the end of a 28 day period. This brings it in line with the present 28 day testing of cylinders. It is customary to have control specimens for each group of test specimens. The dynamic modulus of elasticity of both the test and control specimen is determined by the sonic method at the 9 day age.

The test specimens can be removed daily from the apparatus and the dynamic modulus again determined. This allows for eleven complete cycles of freezing and thawing every 24 hours. All results are expressed in terms of relative E which is the percentage change in dynamic E. The dynamic E at zero cycles is taken at 100 percent. Freezing and thawing cycles are continued until the relative E has decreased to 50% of that at the 9 day age or until the test has been continued to a specified number of cycles. When the freeze-thaw testing has been completed and the final determination of E has been made the specimens are tested in flexure by mid-point loading. The dynamic E and flexural strength of the control specimen is also determined at this time. The durability factor (DFE) based on dynamic modulus of elasticity, and the durability factor (DFM) based on the modulus of rupture are calculated from the following formulas.

$$DFE = \frac{PN}{M}$$

where DFE = durability factor in percent of the dynamic modulus of elasticity at 0 cycles.

P = relative dynamic modulus of elasticity or greater

N = number of cycles at which P reaches 50 percent or the ultimate number of cycles of the test if P does not reach 50% prior to the ultimate cycle,



M = ultimate number of cycles of the test

$$DFM = \frac{M_2}{M_1} \times 100$$

where DFM = durability factor in percent based on the modulus of rupture of stored specimen

M<sub>2</sub> = modulus of rupture of the frozen and thawed specimens in pounds per square inch, and

M<sub>1</sub> = modulus of rupture of the stored control specimens in pounds per square inch.



## CHAPTER IV

THE LABORATORY CONCRETE MIXERDescription of Mixer

The laboratory concrete mixer is a 0.5 cubic foot tilting drum type mixer (Figure 22). It was designed as a scale model of the mixers used on the Grand Coulee Dam. The mixer is powered by a  $1/3$  H.P. electric motor and is operated at a speed of 20 revolutions per minute.



Figure 22. Laboratory Concrete Mixer



### Mixer Tests

Efficiency tests<sup>5</sup> run on the mixer indicated that a mixing period of 5 minutes gives the most uniform and consistent results.

Tests were run on the mixer prior to its use in the investigation to determine its suitability for mixing air-entrained concrete. Comparative tests were run between the laboratory mixer and a  $\frac{1}{2}$  cubic yard field mixer. Identical mixes of normal concrete and air-entrained concrete were mixed by the two mixers. Air content determinations were run on the concrete as well as test cylinders. Air entrainment was obtained by the use of both air-entraining cement and air-entraining agents added to the mixer. Results from these tests are given in Table 5.

TABLE 5  
MIXER COMPARISON TEST RESULTS

Mixer	Mix	Slump	% Air	Compressive Strength 7 day psi
Field Mixer	Normal	2"	1.1	
Lab Mixer		3"	1.2	
Field Mixer	Air-entrain- ing cement	1"	1.8	833 900
Lab Mixer		3 $\frac{1}{2}$ "	2.1	800 750
Field Mixer	Air-entrain- ing Agents	1"	4.2	1450 1535
Lab Mixer		1"	4.3	1140 1250

<sup>5</sup> Laboratory Mixer Efficiency Tests, C.E. 66 Laboratory Report, 1946-47, J.F. Hunt and K.R. Lauer



The results indicated that the laboratory mixer entrained air contents comparable to those obtained with the field mixer. A reasonable check was also obtained between the cylinder results although more tests should be conducted on strength comparisons.

This comparison with the field mixer is of definite value as it allows for a direct correlation of the results of the investigation to field conditions.



## PART II LABORATORY INVESTIGATION

### SYNOPSIS

The purpose of the laboratory work carried out was to investigate air-entrainment in concrete and to determine its effect on durability.

Cylinder compression tests and beam flexural tests were used to determine the effect of air-entrainment on the strength characteristics of concrete.

The effect of entrained air on the workability of concrete was evaluated by slump and flow tests as well as by visual descriptions.

Freeze-thaw tests and scaling tests were used to bring out the effect of entrained air on the durability of concrete. The sonic method of obtaining the modulus of elasticity of concrete beams was used to evaluate the effect of freeze-thaw cycles on concrete beams. The loss in weight accompanying the freeze-thaw cycles was also used as a means of comparison.



## CHAPTER I

MATERIALS AND MATERIAL TESTS

The aggregates used in this investigation were obtained locally from stockpiles in general use in the Edmonton area.

The coarse aggregate used in all mixes was that of Alberta Concrete Products with a grading up to 1". The physical properties of the aggregate are given in Table 6.

TABLE 6

## PHYSICAL PROPERTIES OF COARSE AGGREGATE

Material	Physical Properties			
	Absorption (24 hr.) % by weight	Specific Gravity		
		Bulk Sp. Gr.	Apparent Sp. Gr.	Bulk (Sat. & surf.dry)
Coarse Aggregate	1.3%	2.55	2.60	2.64

Coarse Aggregate Retained on Screen as Indicated			
1"	$\frac{3}{4}$ "	$\frac{3}{8}$ "	4"
0	12	80	98

In gravel evaluation tests the aggregate was found to give expected compressive strengths.



TABLE 7  
AGGREGATE EVALUATION TEST RESULTS

Slump	W/C	Compressive Strength		Expected 28 day
		7 day	28 day	
3"	0.59	2070*	3280*	3200

\* average of two cylinders

Washed Doncaster and Elk Island Sand were used as fine aggregate in the investigation. The physical properties of the sands are given below in Table 8.

TABLE 8  
PHYSICAL PROPERTIES OF FINE AGGREGATE

Material	Lot	Physical Properties				Color Test
		Absorption (24 hr.) % by weight	Specific Gravity			
			Bulk	Bulk (sat.)	Apparent	
Washed Doncaster Sand	1	.60	2.60	2.62	2.65	#2-#3
	2	.60	2.60	2.62	2.65	#1
Elk Island Sand		.81	2.60	2.62	2.65	#1

Material	Lot	Percent Retained on Screen Indicated						
		4	8	16	30	48	100	F.M.
Washed Doncaster Sand	1	5.0	12	21	54	93	98	2.84
	2	8	18.6	28.6	60.6	93	98	3.07
Elk Island Sand		8.8	15.6	25	47	88	97	2.82



A.S.T.M. - C87 - 46 Mortar cube tests were run on the two sands as well as on standard Ottawa sand. The results were given below in Table 9.

TABLE 9  
SAND TESTS A.S.T.M. C87-46

Material	Date Cubes made	Lot	Amt. of sand added grams.	Compressive Strength		
				3 day	7 day	28 day
Standard	Jan.26/48		1721	1030	1410	3870
	Jan.12/48		1717	800	1580	3940
	Jan.26/48		1773	890	1660	3430
Washed	Jan.26/48	2	1664	1020	1450	3800
Doncaster	Jan.15/48	2	1651	773	1760	3550
	Jan.15/48	2	1596	956	1836	3470
	Jan.16/48	2	1646	925	1810	3460
	Nov.7/47	1	1496		1525	3130
	Nov.14/47	1	1193		1507	2630
	Nov.20/47	1	1500		1717	3200
Elk Island	Jan.12/48		1596	713	1595	3600
	Jan.14/48		1537	820	1415	3410

Average of 2 cubes

Average of 3 cubes

Normal Portland Exshaw Cement was used throughout the investigation. The physical properties of the cement used are given below in Table 10.

TABLE 10  
PHYSICAL PROPERTIES OF CEMENT

Specific Gravity	Soundness Pats	Time of Set				Water for Consistency %
		Initial		Final		
		hr.	min.	hr.	min.	
3.13	o.k.	2	45	5	30	24.8



A.S.T.M. C109-44 compressive strength test and S.T.M. C190-44.

Tensile strength tests were run on the cement.

TABLE 11  
COMPRESSIVE STRENGTH TEST RESULTS

Proportions	Flow %	Compressive Strength		
		3 day	7 day	28 day
Cement 500 grs.		635	1190	2940
Sand 1375 "	100%			
Water 245 grs.		643	1330	2820
Cement 500 grs.		720	1280	2750
Sand 1375 grs.	115%			
Water 300 grs.		785	1500	2830

Tensile Strength		
3 day	7 day	28 day
197	307	375
188	290	440
215	330	405
190	305	427

The mixing water used was taken directly from the Edmonton Water System.

Three commercial admixtures were used in the investigation.

Pozzolith manufactured by the Master Builders Company,  
Cleveland, Ohio.

Darex Air-entraining Agent, manufactured by the Dewey and  
Almy Chemical Company, Cambridge, Mass.

Ayr-Trap Air-entraining Agent, manufactured by the A.C. Horn C.,  
Toronto, Canada.



## CHAPTER II

GENERAL LAYOUT OF TESTING PROGRAM

Two series of tests were conducted on each of two lots of Doncaster washed sand. The two series of tests on a particular lot were conducted on different days. One series of tests was made using Elk Island sand.

Five air-entrained mixes and one normal mix were used in each series of tests. Pozzololith was added as suggested by the producer. Darex was added to give one mix with approximately 3 per cent air and one with approximately 6 per cent air. Ayr Trap was added to give two mixes with similar air contents.

The specimens prepared during each test and their identification are given in Table 12.



TABLE 12  
SPECIMEN IDENTIFICATION

Specimen		Identification					
		Nor- mal Mix	Darex 3% Air Mix	Darex 6% Air Mix	Pozz- olith Mix	Ayr- Trap 3% Air Mix	Ayr- Trap 6% Air Mix
Pour 1	1 - 7 day cylinder	NMA1	D3A	D6A	PA	A3A1	A6A
Lot 1	4 - 28 day cylinders	NMB1	D3B1	D6B1	PB1	A3B1	A6B1
Doncaster	2 - 3 mo. cylinders	NMC1	D3C1	D6C1	PC1	A3C1	A6C1
Sand	2 - 1 yr. cylinders	NMD	D3D1	D6D1	PD1	A3D1	A6D1
Mix 1	1 - Freeze-thaw beam	NM1	D31	D61	P1	A31	A61
	1 - Flexural Test beam	NM1	D31	D61	P1	A31	A61
	1 - Slab	NM1	D31	D61	P1	A31	A61
Pour 1	1 - 7 day cylinder	NMA2	D3A2	D6A2	PA2	A3A2	A6A2
Lot 1	3 - 28 day cylinders	NMB5	D3A5	D6A5	PB5	A3B5	A6B5
Doncaster	1 - Freeze-thaw beam	NM2	D32	D62	P2	A32	A62
Sand	1 - Flexural Test beam	NM2	D32	D62	P2	A32	A62
Mix 2	1 - Slab	NM2	D32	D62	P2	A32	A62
Pour 2	1 - 7 day cylinder	NM2A/	D32A1	D62A1	P2A1	A32A1	A62A1
Lot 2	3 - 28 day cylinders	NM2B1	D32B1	D62B1	P2B1	A32B1	A62B1
Doncaster	1 - Freeze-thaw beam	NM21	D321	D62	P21	A321	A621
Sand	1 - Flexural Test Beam	NM21	D321	D62	P21	A321	A621
Mix 1	1 - Slab	NM21	D321	D62	P21	A321	A621
Pour 2	1 - 7 day cylinder	NM2A2	D32A	D62A2	P2A2	A32A2	A62A2
Lot 2	3 - 28 day cylinders	NM2B4	D32B4	D62B4	P2B4	A32B4	A62B4
Doncaster	1 - Freeze-thaw beam	NM22	D322	D322	P22	A322	A622
Sand	1 - Flexural Test beam	NM22	D322	D322	P22	A322	A622
Mix 2	1 - Slab	NM22	D322	D322	P22	A322	A622
Pour 3	1 - 7 day cylinder	ENMA	ED3A	ED6A	ED8A		
Elk Island	3 - 28 day cylinders	ENMB	ED3B1	ED6B1	ED8B1		
Sand	1 - Freeze-thaw beam	ENM	ED3	ED6	ED8		
	1 - Slab	ENM	ED3	ED6	ED8		



## CHAPTER III

MIX DESIGNS; CONCRETE AND SPECIMEN MANUFACTUREMix Designs

All mixes used in the investigation were designed for a cement content of 5 bags per cubic yard. The slump of the normal mix was 3 inches. The workability of the air-entrained mixes was made comparable to that of the normal mix by having equivalent flow as obtained by the A.S.T.M. C124 - 39 flow test.

The design of the normal mix was carried out according to the A.C.I. Mix Design Procedure<sup>6</sup>, as follows:

Materials

Cement	-	Exshaw Standard Portland Specific Gravity 3.13
Sand	-	Doncaster washed Specific Gravity 2.62 Fineness Modulus 2.84
Gravel	-	Alberta Concrete Products Specific Gravity 2.60 Maximum size $\frac{3}{4}$ "
Cement Content	-	5 bags/cubic yard
Slump	-	3 inches

Determination of Trial Mix proportions

$$\text{Cement content} = 5 \times 87.5 = 438 \text{ lbs.} = \frac{438}{62.4 \times 3.13} = 2.24 \text{ cu.ft.}$$

$$\text{Water content} = 300\% = \frac{300}{62.4} = 4.81 \text{ cu. ft.}$$

$$\text{Absolute Volume of Water \& Cement} = 2.24 + 4.81 = 7.05 \text{ cu.ft.}$$

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<sup>6</sup> Journal of the American Concrete Institute, November, 1943.



Absolute Volume of Total Aggregate

$$= 27 - 7.05 = 19.95 \text{ cu. ft.}$$

Absolute Volume of Sand

$$= \frac{47}{100} \times 19.95 = 9.4 \text{ cu. ft.} = 9.4 \times 62.4 \times 2.62$$

$$= 1540 \text{ lbs. sand}$$

Absolute Volume of Gravel

$$= 19.95 - 9.4 = 10.55 \text{ cu. ft.} = 10.55 \times 62.4 \times 2.60$$

$$= 1710 \text{ lbs.}$$

#### Trial Mix Proportions

$$\frac{438}{438} : \frac{1540}{438} : \frac{1710}{438}$$

$$1 : 3.52 : 3.91$$

$$\text{Wt./cubic yard} = 3980 \text{ lbs.}$$

Trial batches proved the mix to be well designed. The 47 percent sand was found to be the optimum sand content for the normal mix.

The normal mix was redesigned for use as an air-entrained mix as suggested by W.A. Gordon<sup>7</sup>. The sand content, by weight of total aggregate, was reduced one percent for each percent of air entrained. The water content was reduced in each case to give a flow equivalent to that of the normal mix.

Trial batches were run to find the quantity of admixture required to give the desired air contents (See Table 13).



TABLE 13

Admixture	Amount Added to 75 lb. batch	Amount Added per cubic yard	Expected Air Content
Pozzolith	44 grams	1#/bag cement	2. to 3%
Darex	2 cc.	3.6 fluid oz.	3%
Darex	6 cc.	10.8 " "	6%
Darex	12 cc.	21.6 " "	7.5%
Ayr-Trap	2 cc.	3.6 " "	3%
Ayr-Trap	5 cc.	9 " "	6%

#### Concrete and Specimen Manufacture

The sand and gravel were taken up from the storage bins in quantities sufficient for the particular day's tests. Moisture contents were taken regularly on both the fine and coarse aggregate. All proportions were weighed to the nearest ounce. Mixing was accomplished in the laboratory 0.5 cubic foot tilting drum mixer. Half of the mixing water was first added to the mixer, followed by the coarse aggregate. The cement and sand premixed by hand were then added followed by the rest of the mixing water. The admixtures Darex and Ayr-Trap were added to the water. Pozzolith was added to the sand cement mixture. The batches were mixed for five minutes. Timing of mixing started when all materials including water had entered the drum. The number of batches required for each test were mixed in quick succession in the mixer, and then combined by hand mixing with a shovel. A constant check was kept on the consistency of the concrete by running a slump test and flow test on each mix. The workability of the concrete was also evaluated descriptively.



The specimens prepared from each mix are outlined in Table 13. All specimens were prepared according to A.S.T.M. standards. The specimens were tested and cured as follows:

Cylinders - all cylinders poured were 6" x 12" in size. They were stripped at 24 hours and cured in water till time of test. Tests were carried out at 7 days, 28 days, and 3 months. All testing was carried out in a 200,000 pound range Baldwin testing machine.

Beams - the  $3\frac{1}{2}$ " x  $4\frac{1}{2}$ " x 16" beams were stripped at 24 hours and cured an additional twenty-seven days in water. One beam from each mix was then tested for flexural strength using a concentrated load applied at the mid point. (See Figure 23).



Figure 23. Beam tested in Tension



Slabs - forms stripped at 24 hours, then cured for an additional 27 days, until time of test. (Scaling Test).



## CHAPTER IV

PLASTIC CONCRETE TESTS AND OBSERVATIONS

The basic mixes (see Table 14) were designed to develop a slump of 3 inches. The actual slumps obtained varied from 2.5 inches to 3.5 inches. In an effort to keep the workability of the various air-entrained mixes similar to that of the normal mix the flow test was used in conjunction with the slump test. A flow of 70% was found to be equivalent to a 3-inch slump for the normal mix. This relationship was found to differ very little for the air-entrained mixes. As the air content of the mixes increased the slump required for a 70% flow decreased slightly. At constant slump and flow the air entrained mixes became appreciably more workable. The entrained air made the mixes more cohesive and plastic, as well as making them more rodable. Small amounts of segregation were evident in the flow test. No trace of segregation was evident while handling the air entrained mixes.

Constant amounts of air entraining agents were used throughout the investigation. Considerable variation was obtained in the resulting air contents. A decrease of approximately one per cent in air content occurred in the tests conducted on lots 1 and 2 of Doncaster Sand. This decrease can be accounted for by the difference in grading of the sands used in the two pours. Lot 1 of washed Doncaster Sand was used in pour 1. It had some 46% passing sieve #30. Lot 2 of washed Doncaster Sand used in pour 2 has only 39% passing sieve #30. The percentages passing sieves 48 and 100 are the same for both sands. Thus the sand from lot 1 has some 7% more passing sieve #30 than the sand of lot 2. According to data published by H.L. Kennedy<sup>8</sup> this change in sand grading could account for some

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<sup>8</sup> The Function of Entrained Air in Portland Cement, Proc. A.C.I. Vol. 40, 1944.



TABLE 14  
CONCRETE MIXTURE DATA

Admix- ture	Cement Factor Bags/cubic yard		W/C by wt.	% Air	V/C by vol.	% Sand
	Theoret- ical	Actual				
Pour 1 Mix 1	NM1	5	5.0	.71	1.55	2.43 47.5 ✓
	D31	5	4.98	.60	4.05	2.32 45.0
	D61	5	5.05	.595	6.6	2.56 43.5
	A31	5	5.02	.677	3.4	2.48 45.0
	A61	5	5.16	.575	5.0	2.33 44.5
	P1	5	5.04	.616	2.7	2.23 46.2
Pour 1 Mix 2	NM2	5	4.93	.705	1.50	2.39 47.5 ✓
	D32	5	4.91	.636	4.1	2.45 44.5
	D62	5	5.05	.585	6.7	2.55 43.5
	A32	5	5.10	.66	2.7	2.36 46.0
	A62	5	5.17	.56	5.2	2.30 44.5
	P2	5	5.04	.62	.21 2.1	2.19 46.2
Pour 2 Mix 1	NM21	5	5	.725	1.0	2.4 47.3
	D321	5	5.1	.636	2.9	2.32 45.5
	D621	5	5.1	.605	6.0	2.55 43.5
	A321	5	5.15	.612	2.0	2.14 45.5
	A621	5	5.2	.565	3.9	2.19 43.7
	P21	5	5.15	.582	1.9	2.03 46
Pour 2 Mix 2	NM22	5	5.03	.65	1.1	2.15 47
	D322	5	5.15	.59	3.1	2.17 46
	D622	5	5.10	.543	5.8	2.33 43.7
	A322	5	5.10	.61	2.6	2.18 45.5
	A622	5	5.15	.567	4.2	2.25 43.7
	P22	5	5.04	.583	2.1	2.07 46.5
Pour 3	ENM	5	5	.67	1.25	2.27 47.2
	ED3	5	5.05	.604	3.6	2.27 45.5
	ED6	5	5.10	.563	6.2	2.44 43.8
	ED8	5	5.16	.543	7.5	2.50 42.4



0.4% change in air content. There is a fundamental difference between the natural air content of a mix and the entrained air content of a mix. The entrained air consists of minute sized air bubbles entrained amongst the fine sand particles. These air bubbles act as very efficient fine aggregate and have a marked effect on the workability of the mix. The natural air content, however, is air entrained mechanically by mixing. It consists of large air voids which have little or no effect on the workability of the mix. The amount of air entrained is dependent on the structure of the plastic mix which is in turn dependent on the grading and shape of aggregate used. As a result a change in sand grading can have an effect on the natural air content of a mix as well as on the entrained air content. This is the case with the sands of lot 1 and lot 2. The normal mix using sand from lot 2 has an air content of only 1.1% as compared to 1.5% with sand of lot 1. This 0.4% reduction in normal air content would also show up in the total air content of the air-entrained mixes. As a result the change in sand grading will account for some 0.4% decrease in the normal air content and some 0.4% decrease in the entrained air content.

The air contents obtained by using Ayr-Trap air-entraining agent vary considerably from mix to mix. Variations as great as 0.6% in an air content of 3% were obtained from two identical mixes. Darex proved very stable as an air entraining agent. Air contents were found to vary only 0.1% to 0.2% from mix to mix. Pozzolite gave consistent air contents in the second pour but the air contents varied some 0.6% in pour 1.

The effect of the admixtures used on the water-cement ratio in gallons per bag of cement are given in Table 15. Pozzolite has the greatest effect reducing the water-cement ratio about 1 gallon per bag of cement for an increase of each one per cent in air content. Ayr-Trap reduced the water-cement ratio about 1 gallon per bag of cement for an



TABLE 15

## EFFECT OF ADMIXTURES ON WATER-CEMENT RATIO

	Admixture	% Sand by vol.	% Air	W/C Imp. g.p.b.	Reduction Imp. g.p.b.
Pour 1 Mix 1	NM1	47.5	1.55	6.20	0
	D31	45.0	4.05	5.25	.95
	D61	43.5	6.6	5.20	1.00
	A31	45.0	3.4	5.92	1.28
	A61	44.5	5.0	5.04	1.16
	P1	46.2	2.7	5.38	.82
Pour 1 Mix 1	NM2	47.5	1.50	6.16	0
	D32	44.5	4.1	5.56	.60
	D62	43.5	6.7	5.12	1.04
	A32	46.0	2.7	5.77	.39
	A62	44.5	5.2	4.91	1.25
	P2	46.2	2.1	5.42	.74
Pour 2 Mix 1	NM21	47.3	1.0	6.34	0
	D321	45.5	2.9	5.56	.78
	D621	43.5	6.0	5.29	1.05
	A321	45.5	2.0	5.35	.99
	A621	43.7	3.9	4.94	1.40
	P21	46.0	1.9	5.08	1.26
Pour 2 Mix 2	NM22	47	1.1	5.70	0
	D322	46	3.1	5.16	.54
	D622	43.7	5.8	4.75	.95
	A322	45.5	2.6	5.33	.37
	A622	43.7	4.2	5.67	1.03
	P22	46.5	2.1	5.10	.60
Pour 3	ENM	47.2	1.25	5.85	0
	ED31	45.5	3.6	5.29	.56
	ED6	43.8	6.2	4.93	.92
	ED8	42.4	7.5	4.75	1.10



increase in air content of 2 to 4%. For increases in air contents of from 2 to 2.5% Darex seems to have a varying effect on the water-cement ratio. Reductions of 0.5 to 1 gallon per bag of cement were obtained. For an increase of 5% in air content using Darex a consistent reduction of 1 gallon per bag of cement was obtained. This ability to reduce the water-cement ratio is the controlling factor in the relationship between the air entrained in a mix and the resulting strength of the hardened concrete. The larger the reduction per per cent increase in air content the less adverse effect the entrained air will have on the strength of the concrete.



## CHAPTER V

### STRENGTH TESTS

The cylinder test results of the investigation are given in Tables 16, 17, 18, 19, and 20. The influence of the various admixtures, in the amounts used, on the compressive strength is shown in Table 21. All air-entrained mixes used gave compressive strengths greater than those of the normal mix except the 6% Darex mix 1 of pour 1, where the 28-day and 3-month cylinder results were lower than the normal. The 3% Ayr-Trap mix of mix 1, pour 1, also gave 3-month cylinder results lower than those of the normal mix. The 6% Darex mix had an air content of 6.6% which is in the range where losses in strength can be expected. The Pozzolith mix shows a large increase in strength at the early ages. This could be expected because of the large reduction in water accompanying its use and because of the accelerator incorporated in the admixture. The Ayr-Trap mixes gave good strength increases over those of the normal mixes. The strengths increased with increases in air content for the range of air contents used. This is due to the large reduction in water demand resulting from the use of Ayr-Trap. The beneficial effect on strength resulting from the use of the admixtures falls off with age. This is particularly evident from the 3-month cylinder results. (See Figures 24 and 25). The effect of the accelerator in Pozzolith is very evident in Figure 25.

Plots of water-cement ratio versus compressive strength were made from the results. (Figures 26 and 28). Different plots were made for each pour because of the variation in cylinder strengths obtained from pour 1. These variations were due to organic material in the sand. Plots of void-cement ratio versus compressive strength were also made, (Figures 27 and 29). These plots are not very informative because of the small



range of compressive strengths used. As a result of this small range of compressive strengths only horizontal groupings of points were obtained. The plots due, however, indicate a better relationship between void-cement ratio and strength than between the water-cement ratio and compressive strength. This is in accord with the generally accepted view that the void-cement ratio is the controlling factor in air-entrained concrete mix design rather than the water-cement ratio.

The influence of the various admixtures on the flexural strength of concrete is shown in Table 22. The results shown are values obtained on  $3\frac{1}{2}$ " x  $4\frac{1}{2}$ " x 16" beams tested at 28 days. The data indicate that none of the admixtures used exert an appreciable adverse influence on the flexural strength of the concrete.



TABLE 16  
CYLINDER RESULTS

Cylinder No.	Age	Ultimate Load	Compressive Stress p.s.i.
NMA1	7 day	27,700	940
NMA2	7 day	27,750	990
B1	28 day	68,600	2450
B2	28 day	70,500	2510
B3	28 day	64,000	2290
B4	28 day	64,000	2290
B5	28 day	60,400	2160
B6	28 day	54,000	1930
B7	28 day	50,800	1960
B8	28 day	50,400	1945
B9	28 day	65,400	2340
C1	3 mo.	103,000	3680
C2	3 mo.	97,000	3460
NM2A1	7 day	38,400	1370
NM2A2	7 day	40,000	1430
B1	28 day	70,500	2520
B2	28 day	73,200	2610
B3	28 day	75,000	2680
B4	28 day	79,100	2820
B5	28 day	78,000	2790
B6	28 day	77,500	2760
D3 A1	7 day	35,950	1285
D3A2	7 day	28,500	1020
B1	28 day	63,700	2280
B2	28 day	74,000	2640
B3	28 day	77,500	2770
B4	28 day	68,000	2430
B5	28 day	53,000	1890
B6	28 day	76,000	2710
B7	28 day	70,300	2510
C1	3 mo.	105,200	3760
C2	3 mo.	112,800	4030
D32A1	7 day	44,000	1600
D32A2	7 day	42,000	1525
B1	28 day	87,300	3110
B2	28 day	93,600	3340
B3	28 day	87,100	3100
B4	28 day	89,100	3180
B5	28 day	86,300	3080
B6	28 day	84,000	3000



TABLE 17  
CYLINDER RESULTS

Cylinder No.	Age	Ultimate Load	Compressive Stress p.s.i.
PA1	7 day	42,350	1515
PA2	7 day	42,250	1510
PB1	28 day	82,700	2950
B2	28 day	78,000	2790
B3	28 day	82,300	2940
B4	28 day	70,400	2520
B5	28 day	84,700	3030
B6	28 day	82,000	2930
B7	28 day	87,800	3130
C1	3 mo.	106,000	3800
C2	3 mo.	97,500	3480
P2A1	7 day	60,500	2160
P2A2	7 day	69,100	2470
P2B1	28 day	99,800	3560
B2	28 day	101,800	3640
B3	28 day	97,200	3470
B4	28 day	95,600	3410
B5	28 day	102,600	3660
B6	28 day	95,000	3390
D6A1	7 day	28,050	1000
A2	7 day	29,800	1065
B1	28 day	53,600	1915
B2	28 day	54,100	1930
B3	28 day	57,700	2060
B4	28 day	56,100	2000
B5	28 day	62,500	2230
B6	28 day	58,500	2090
B7	28 day	59,600	2130
B8	28 day	65,500	2340
C1	3 mo.	84,900	3030
C2	3 mo.	84,500	3020
D62A1	7 day	41,500	1480
D62A2	7 day	43,200	1540
D62B1	28 day	84,800	3030
B2	28 day	85,000	3035
B3	28 day	85,200	3040
B4	28 day	81,500	2910
B5	28 day	81,700	2915
B6	28 day	78,000	2780



TABLE 18  
CYLINDER RESULTS

Cylinder No.	Age	Ultimate Load	Compressive Stress p.s.i.
A3A1	7 day	29,150	1040
A3A2	7 day	38,100	1360
A3B1	28 day	60,700	2170
B2	28 day	58,200	2080
B3	28 day	61,200	2190
B4	28 day	62,600	2240
B5	28 day	68,000	2430
B6	28 day	63,400	2260
B7	28 day	63,400	2260
C1	3 mo.	96,300	3440
C2	3 mo.	92,000	3280
A32A1	7 day	45,500	1625
A32A2	7 day	45,800	1640
A32B1	28 day	90,800	3240
B2	28 day	87,400	3120
B3	28 day	89,400	3190
B4	28 day	78,600	2810
B5	28 day	82,800	2950
B6	28 day	80,000	2860
A6A1	7 day	34,350	1190
A6A2	7 day	34,650	1205
A6B1	28 day	73,000	2610
B2	28 day	73,200	2615
B3	28 day	73,800	2640
B4	28 day	74,200	2650
B5	28 day	73,000	2610
B6	28 day	72,200	2580
B7	28 day	68,000	2430
C1	3 mo.	106,000	3790
C2	3 mo.	94,400	3370
A62A1	7 day	51,000	1850
A62A2	7 day	50,600	1810
A62B1	28 day	98,200	3510
B2	28 day	95,500	3410
B3	28 day	93,000	3320
B4	28 day	82,800	2960
B5	28 day	83,500	2980
B6	28 day	83,300	2975



TABLE 19  
CYLINDER RESULTS

Cylinder No.	Age	Ultimate Load	Compressive Stress p.s.i.
ENMA	7 day	35,800	1280
ENMB1	28 day	67,200	2400
ENMB2	28 day	65,100	2320
ENMB2	28 day	67,100	2400
ED3A	7 day	41,800	1490
ED3B1	28 day	63,800	2460
ED3B2	28 day	74,600	2660
ED3B3	28 day	75,700	2700
ED6A	7 day	42,000	1500
ED6B1	28 day	72,100	2580
ED6B2	28 day	70,300	2510
ED6B3	28 day	72,000	2570
ED8A	7 day	37,600	1342
ED8B1	28 day	67,100	2400
ED8B2	28 day	62,300	2230
ED8B3	28 day	71,800	2560



TABLE 20  
SUMMARY OF CONCRETE CYLINDER RESULTS

			Compressive Strength		
	Admixture	% Air	7 day	28 day	3 months
Pour 1 Mix 1	NM1	1.55	990	2045	3570
	D31	4.05	1285	3560	3890
	D61	6.6	1000	1975	3020
	A31	3.4	1040	2150	3360
	A61	5.0	1190	2620	3570
	P1	2.7	1515	2890	3640
Pour 1 Mix 2	NM2	1.5	990	2080	
	D32	4.1	1020	2380	
	D62	6.7	1065	2200	
	A32	2.7	1360	2290	
	A62	5.2	1205	2580	
	P2	2.1	1510	2900	
Pour 2 Mix 1	NM21	1.10	1370	2600	
	D321	3.0	1600	3180	
	D621	6.1	1480	3030	
	A321	2.1	1625	3180	
	A621	4.0	1850	3420	
	P21	2.0	2160	3550	
Pour 2 Mix 2	NM22	1.1	1430	2790	
	D322	3.1	1525	3090	
	D622	5.8	1540	2870	
	A322	2.6	1640	2870	
	A622	4.2	1810	2970	
	P22	2.1	2470	3480	
Pour 3	ENM	1.25	1280	2370	
	ED3	3.6	1490	2600	
	ED6	6.2	1500	2550	
	ED8	7.5	1342	2400	



TABLE 21  
EFFECT OF ADMIXTURES ON COMPRESSIVE STRENGTH

		Strength - Percent			
		C.F. 5 bags/cubic yard		Slump 3"	
		Compressive Strength			
	Admixture	% Air	7 day	28 day	3 months
Pour 1 Mix 1	NM1	1.55	100% (990 psi)	100% (2045 psi)	100% (3570 psi)
	D31	4.05	130.0	125.2	109.0
	D61	6.6	101.0	96.8	84.6
	A31	3.4	105.0	105.0	94.0
	A61	5.0	120.0	128.2	100.0
	P1	2.7	153.0	141.1	102.0
Pour 1 Mix 2	NM2	1.5	100% (990 psi)	100% (2080 psi)	
	D32	4.1	103.1	114.2	
	D62	6.7	107.5	105.8	
	A32	2.7	137.5	110.0	
	A62	5.2	122.0	124	
	P2	2.1	152.5	139.4	
Pour 2 Mix 1	NM21	1.10	100% (1370 psi)	100% (2600 psi)	
	D321	3.0	118.0	122.2	
	D621	6.1	108.0	116.5	
	A321	2.1	118.5	122.2	
	A621	4.0	135.0	131.5	
	P21	2.0	158.0	136.5	
Pour 2 Mix 2	NM22	1.1	100% (1430 psi)	100% (2790 psi)	
	D322	3.1	106.8	110.8	
	D622	5.8	107.8	103	
	A322	2.6	114.8	103	
	A622	4.2	126.7	106.5	
	P22	2.1	173.0	125.0	
Pour 3	ENM	1.25	100% (1280 psi)	100% (2370 psi)	
	ED3	3.6	116.3	109.5	
	ED6	6.2	117.0	107.5	
	ED8	7.5	105.0	101.0	



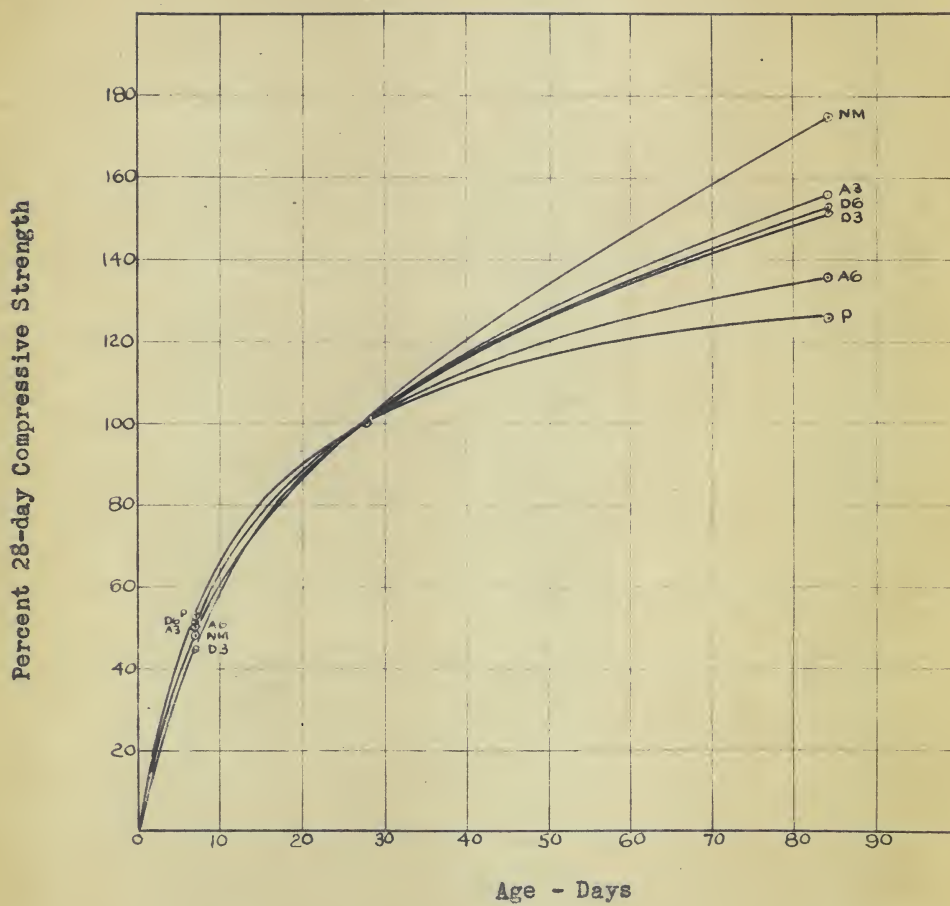


Figure 24. Influence of Admixture on Compressive Strength



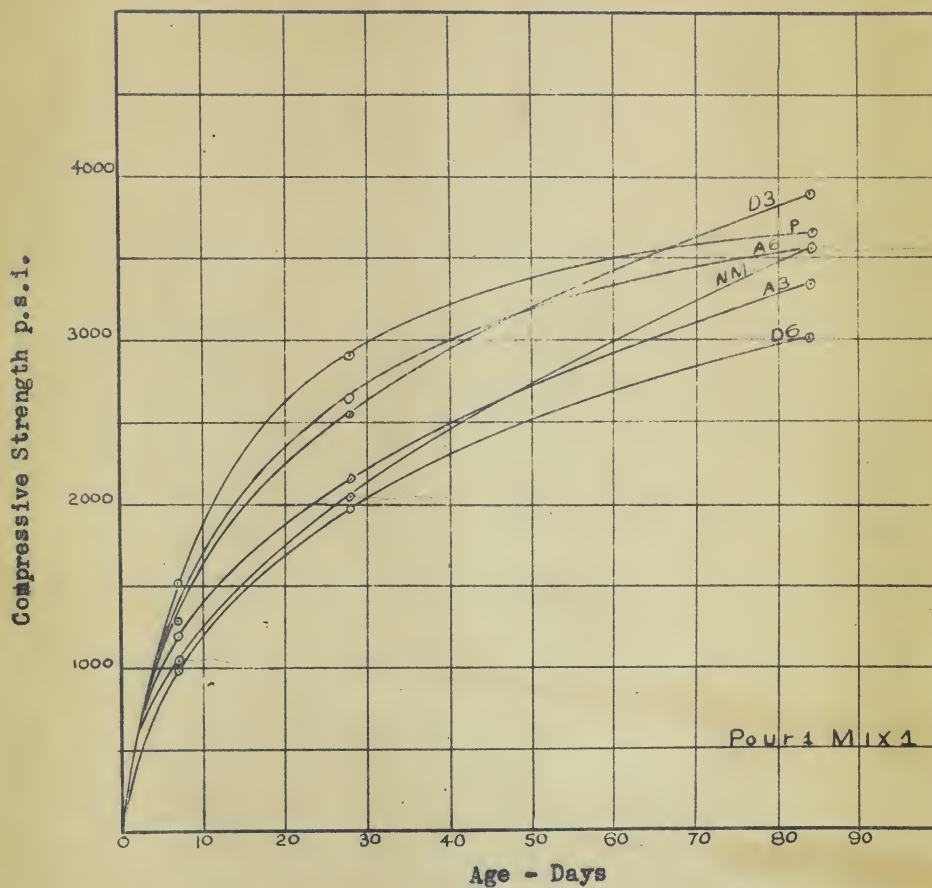


Figure 25. Influence of Admixtures on Compressive Strength



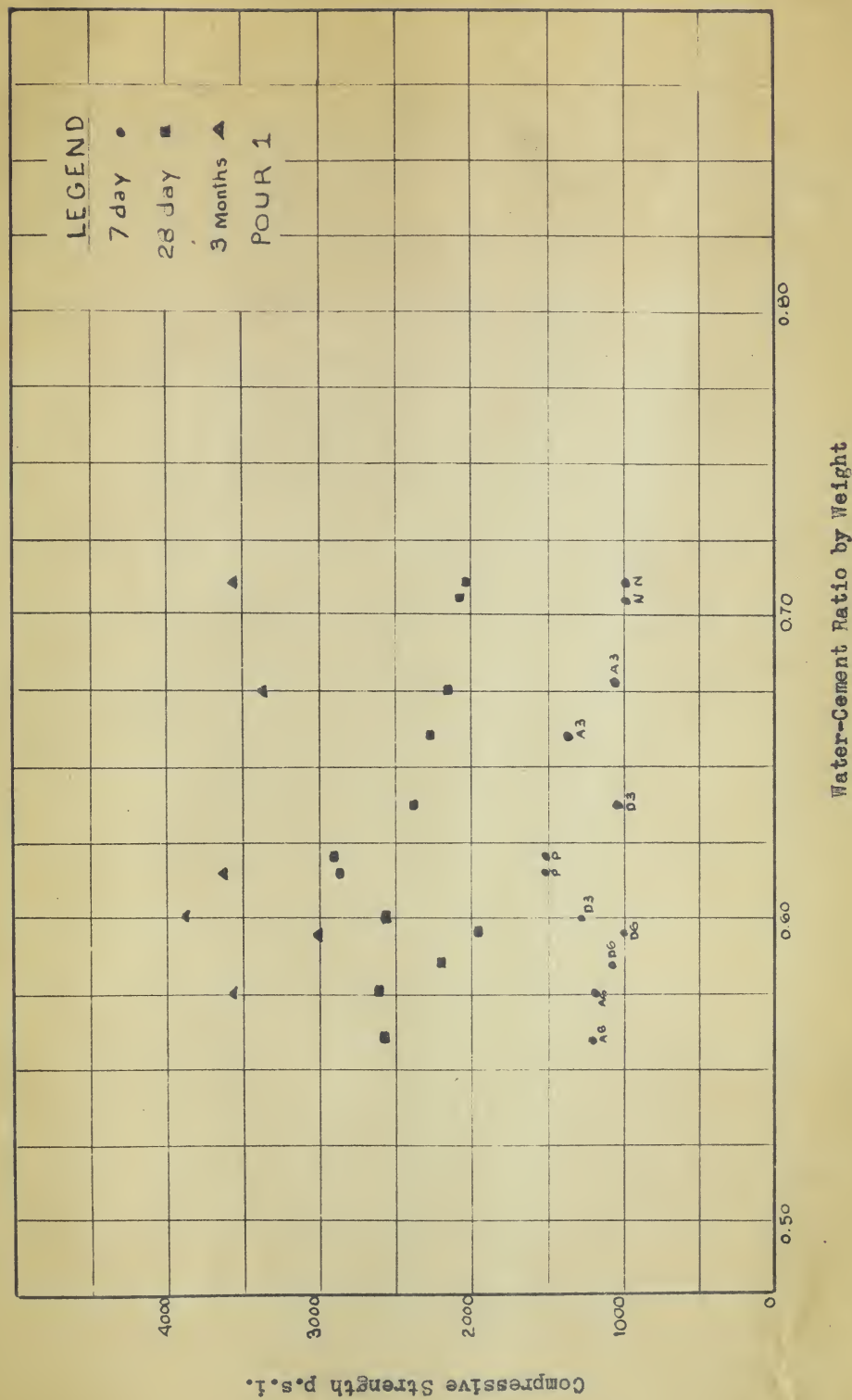


Figure 26. Relation of Water-Cement Ratio to Compressive Strength at Various Ages of Test



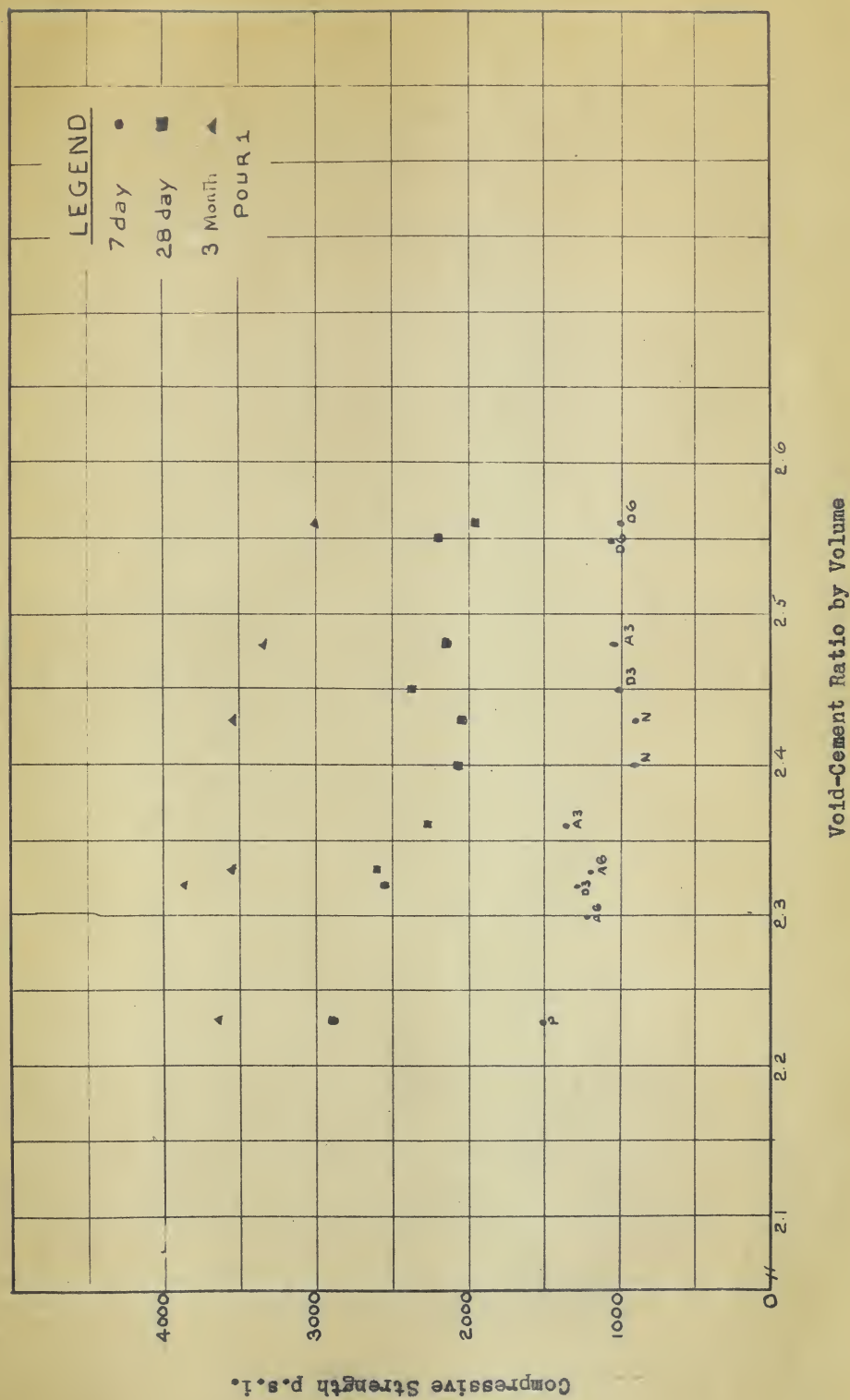


Figure 27. Relation of Void-Cement Ratio to Compressive Strength at Various Ages of Test



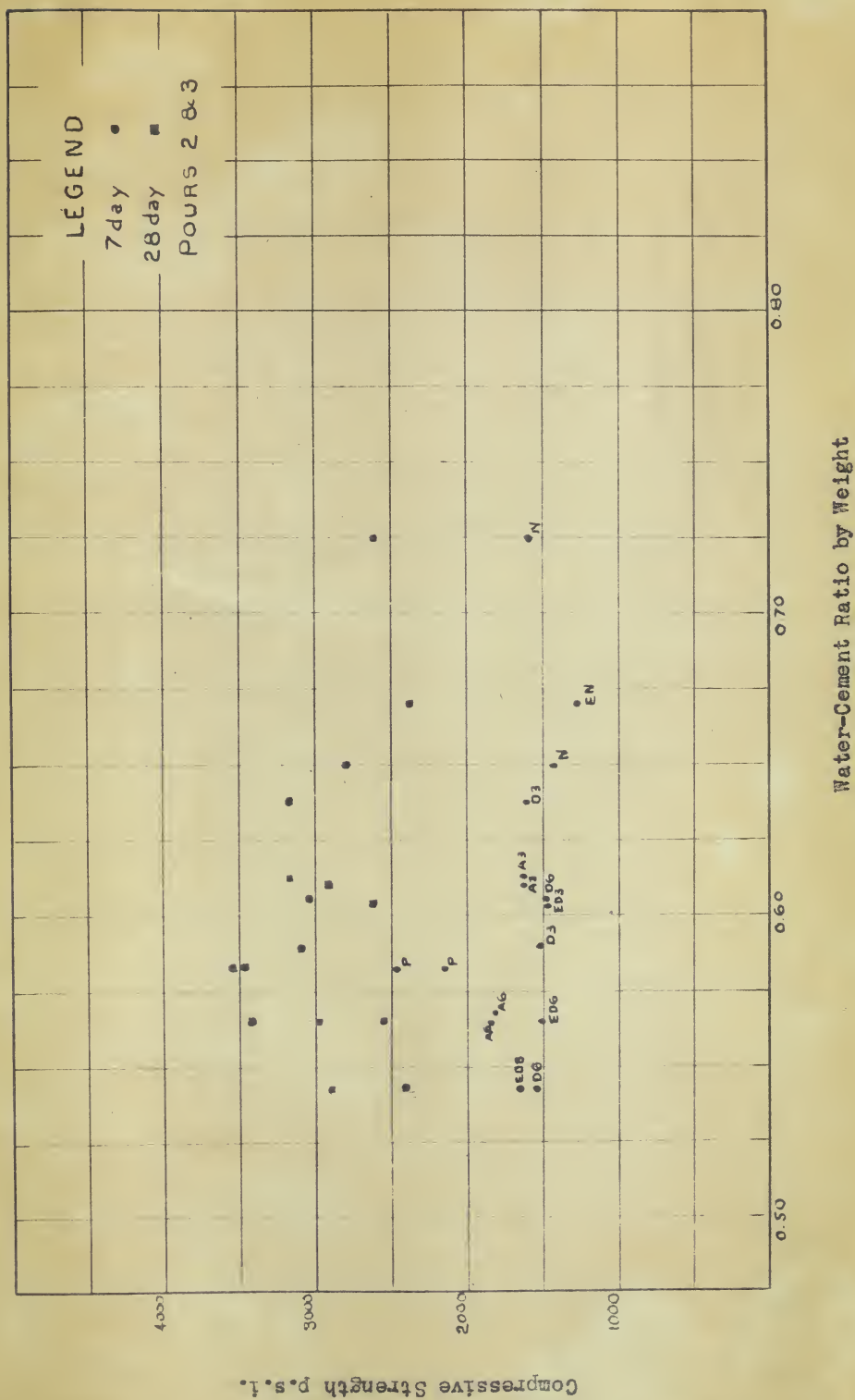


Figure 28. Relation of Water-Cement Ratio to Compressive Strength at Various Ages of Test



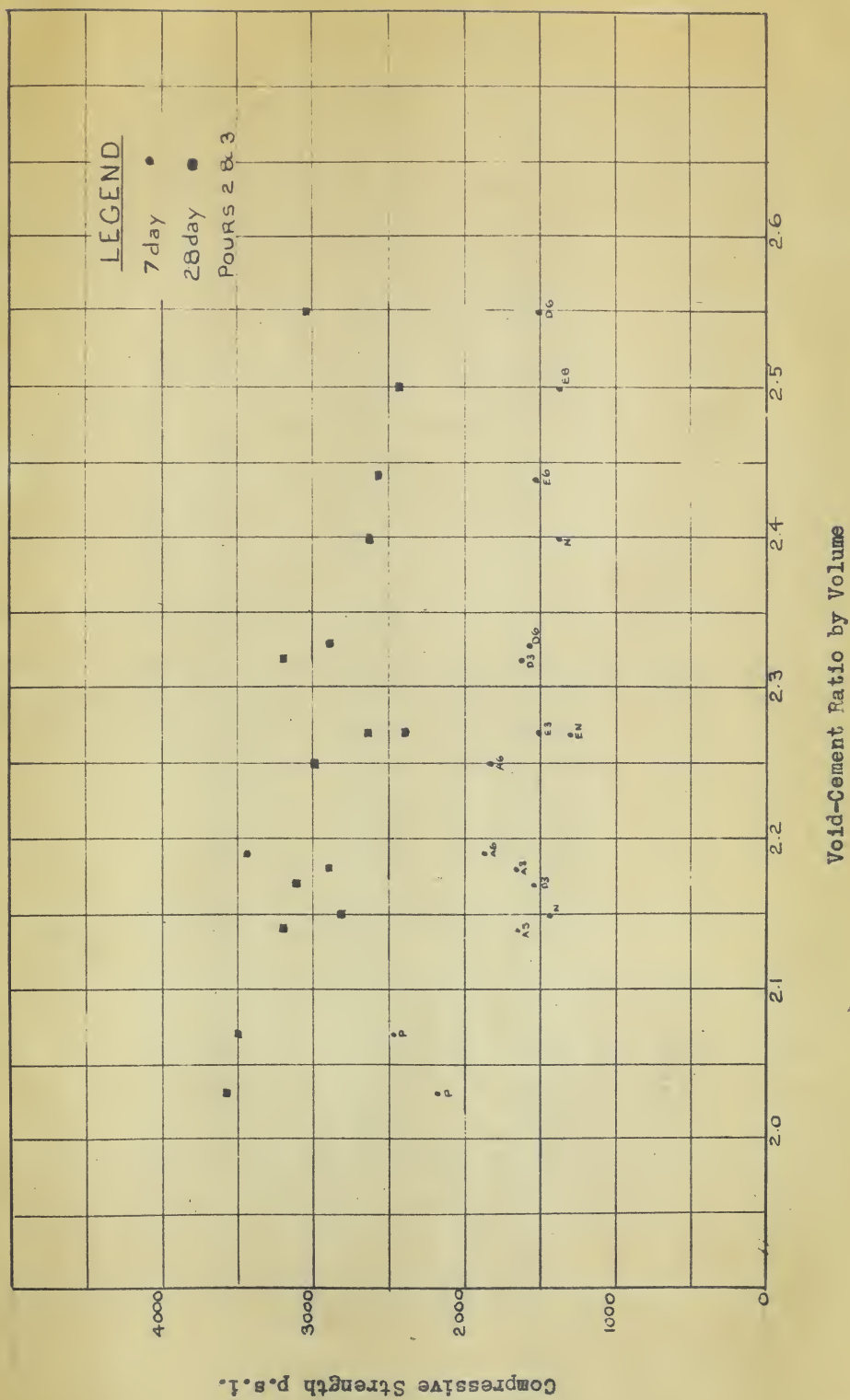


Figure 29. Relation of Void-Cement Ratio to Compressive Strength at Various Ages of Test



TABLE 22  
FLEXURAL STRENGTH RESULTS

	Admixture	% Air	Ultimate Load lbs.	Flexural Strength 28-day p.s.i.	Flexural Strength %
Pour 1	NM1	1.55	1805	542	100%
Mix 1	D31	4.05	1770	532	98.2
	D61	6.6	1740	523	96.6
	A31	3.4	1680	505	93.3
	A61	5.0	2010	605	112.0
	P1	2.7	1810	544	100.5
Pour 1	NM2	1.50	1765	530	100
Mix 2	D32	4.1	2050	603	114.0
	D62	6.7	1725	518	98.0
	A32	2.7	1810	544	102.8
	A62	5.2	1770	532	100.5
	P2	2.1			
Pour 2	NM21	1.0	1600	481	100
Mix 1	D321	2.9	1700	511	106.2
	D621	6.0	2200	661	137.5
	A321	2.0	1960	590	123.0
	A621	3.9	2110	635	132.2
	P21	1.9	2450	736	153.0
Pour 2	NM22	1.1	2280	685	100
Mix 2	D322	3.1	2135	642	94
	D622	5.8	2650	797	116.2
	A322	2.6	1880	718	105
	A622	4.2	2070	565	82.5
	P22	2.1	2390	623	91.0



## CHAPTER VI

### SCALING TESTS

#### Introduction

It is common practice to use rock salt ( $\text{NaCl}$ ) and calcium chloride for ice removal from city pavements. It is particularly important that the ice which forms during cold weather be removed from the grades, at curves, intersections, and around street railway switch points. The increased use of these salts for ice removal has resulted in severe scaling of the pavements. The mixing of the salts with cinders and sand to reduce the concentration of the salt has not solved the problem. The salt accumulates during the course of the winter due to repeated applications, and at times has been found in layers as much as  $\frac{1}{4}$  inch thick. Traffic has a tendency to carry the salt from intersections onto the side streets. In this way the scaling problem becomes fairly widespread, involving considerable maintenance and new construction.

The purpose of this phase of the investigation is to determine the effect of air-entrained in concrete on the resistance of concrete to scaling produced by using salts for ice removal.

#### Testing Procedure

18" x 6" x 2" concrete slabs were used as test specimens. A 1" x 1" dyke was formed around the bottom surface by building up the center portion of the bottom of the form. This gives a test surface 16" x 4". See Figure 30.





Figure 30. Slab Forms for Scaling Test

All test specimens were fabricated by use of a standardized procedure. The forms were covered with a thin film of petroleum to facilitate their removal. The form was then filled with concrete and rodded 25 times. The sides of the slabs were spaded to insure that a water-tight dyke was formed on the bottom surface of the slab. The surface was troweled level with the forms. The slab was then placed in the moist room for 24 hours after which time the forms were removed. The specimens were then allowed to cure under water for an additional 27 days.

At the end of the curing period the slabs were weighed and placed in the cold room for a period of 24 hours. A thin layer of fresh water was then allowed to freeze on the surface of the slab. After approximately 18 hours of freezing the ice surface was covered with 60 grams of calcium chloride. This corresponds to 3 pounds per square yard which does not exceed the quantity generally used in practice. The slabs were allowed to remain in the cold room under the thawing action of the calcium chloride for from 4 to 6 hours. The cold room was kept at  $-18^{\circ}\text{C}$ . During the last hour of the thawing period the salt solution was poured off and the surface brushed with a wire brush, and fresh water again applied to the surface.



The slab was then again frozen for 18 hours. This cycle was repeated every day in the week except Sunday, when the slabs were allowed to freeze some 42 hours.

The calcium chloride used was purchased from local sources. A chemical analysis was obtained on the lot to see if it contained any foreign material. The chemical analysis indicated the calcium chloride to be of very good quality, having only 0.21% of sodium sulphate. Salts used have occasionally been found to contain a high percentage of sodium sulphate. Severe scaling will result from a high sulphate content.

A visual evaluation of the scaling based on the percent of the surface scaled proved satisfactory. The extent of the scaling of the surface of the slabs is indicated by the following rating.

- F.S. - Fine Scaling - scaling off of a fine layer of cement paste from the slab surface.
- L.S. - Light Scaling - scaling off of a thin layer of fine aggregate exposing the coarser particles of fine aggregate as well as the coarse aggregate very near the surface.
- M.S. - Medium Scaling - scaling off of fine aggregate exposing the coarse aggregate.
- H.S. - Heavy Scaling - scaling off of layers of fine aggregate exposing the coarse aggregate to a quarter of its thickness.



TABLE 23  
SLAB SCHEDULE

Set No.	Slab No.	No. Cast	Admixture	% Air
1	NM1	1	None	1.55
Pour 1	D31	1	Darex	4.05
Mix 1	D61	1	Darex	6.6
	P1	1	Pozzololith	2.7
	A31	1	Ayr-Trap	3.4
	A61	1	Ayr-Trap	5.0
Pour 1	NM2	1	None	1.50
Mix 2	D32	1	Darex	4.10
	D62	1	Darex	6.7
	P2	1	Pozzololith	2.1
	A32	1	Ayr-Trap	2.7
	A62	1	Ayr-Trap	5.2
2	NM21	1	None	1.1
Pour 2	D321	1	Darex	3.0
Mix 1	D621	1	Darex	6.1
	P21	1	Pozzololith	2.0
	A321	1	Ayr-Trap	2.1
	A621	1	Ayr-Trap	4.0
Pour 2	NM22	1	None	1.1
Mix 2	D322	1	Darex	3.1
	D622	1	Darex	5.8
	P22	1	Pozzololith	2.1
	A322	1	Ayr-Trap	2.6
	A622	1	Ayr-Trap	4.2
3	ENM	1	None	1.25
Pour 3	ED3	1	Darex	3.6
	ED6	1	Darex	6.2
	ED8	1	Darex	7.5



### Test Results

A series of photographs were taken of six of the slabs of Set 2 and of the four slabs of Set 3 as the scaling tests progressed. See Figures 31, 32, 33, 34, 35, 36, 37 and 38. They give a clear idea of how the scaling progressed under the cycles of freezing and thawing. Slab scaling test results are given in Tables 24 to 28.



Figure 31

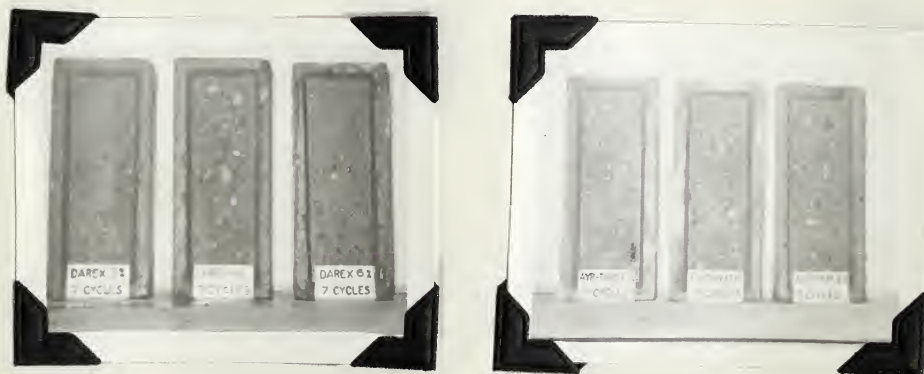


Figure 32





Figure 33



Figure 34



Figure 35





Figure 36

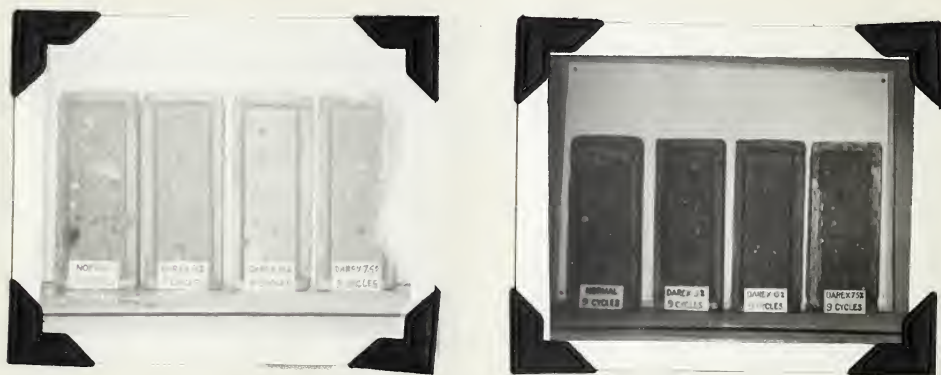


Figure 37

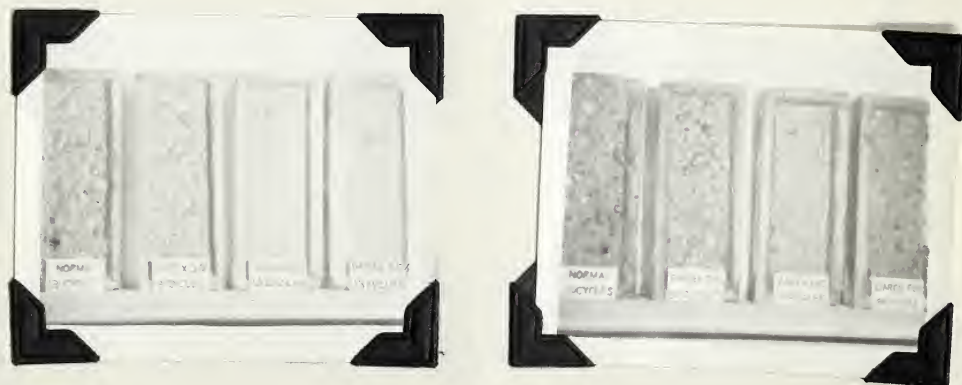


Figure 38



Slab No. NM1	Slab No. D31	Slab No. D61	Slab No. A31	Slab No. A61	Slab No. P1
Cycle Rating No.	Cycle Rating No.	Cycle Rating No.	Cycle Rating No.	Cycle Rating No.	Cycle Rating No.
1	1	1	1	1	1
2	2	2	2	2	2
3	3	3	3	3	3
4	4	4	4	4	4
5	5	5	5	5	5
6	6	6	6	6	6
7	7	7	7	7	7
8	8	8	8	8	8
	9	9	9	9	
	10	10	10	10	
	11	11	11	11	
	12	12			
	13	13			
	14	14			

Table 24. Set 1 Scaling Tests



Slab No. NM1-2	Slab No. D32	Slab No. D62	Slab No. A32	Slab No. A62	Slab No. P2
Cycle No.	Cycle Rating No.	Cycle Rating No.	Cycle Rating No.	Cycle Rating No.	Cycle Rating No.
1	1	1	1	1	1
2	2	2	2	2	2
3	3	3	3	3	3
4	4	4	4	4	4
5	3% F.S.	50% L.S.	5	20% L.S.	5
6	80% H.S.	80% M.S.	6	2% H.S.	6
7	100% H.S.	7	7	20% M to HS	7
		8	8	50% M to HS	8
		9	9	95% H.S.	9
		10	10	100% H.S.	10
		11	11	35% M.S.	11
		12	12	50% H.S.	12
		13	13	100% H.S.	13
				5% H.S.	5
				100% M to HS	100% M to HS
				100% H.S.	100% H.S.
				100% H.S.	100% H.S.

Table 25. Set 1 Scaling Tests



Slab NM21	Slab No. D321	Slab No. D621	Slab No. A321	Slab No. A621	Slab No. P21
Cycle Rating	Cycle Rating	Cycle Rating	Cycle Rating	Cycle Rating	Cycle Rating
No.	No.	No.	No.	No.	No.
1	1	1	1	1	1
2	2	2	2	2	2
3	3	3	3	3	3
4	4	4	4	4	4
5	5	5	5 80% F.S.	5	5 15% H.S.
6 35% H.S.	6	6	6 75% L to HS	6	6 80% L to HS
7 80% H.S.	7 30% F.S.	7	7 90% L to HS	7	7 90% H.S.
8 100% H.S.	8 10% L to HS	8	8 100% H.S.	8 45% L.S.	8 100% H.S.
9	9 50% L to HS	9 70% L.S.	9		
	10 60% H.S.	10 90% L.S.	10	50% H.S.	
	11 75% H.S.	11	11	90% L to HS	
	12 80% H.S.	12 100% L.S.	12	100% L to HS	
	13 100% H.S.	13 100% M.S.	13		
		14 100% M to HS	14		
		15 100% M to HS	15		
		16 100% M to HS	16	100% M to HS	
		17 100% M to HS	17		

Table 26. Set 2 Scaling Tests



Slab No. NM22	Slab No. D322	Slab No. D622	Slab No. A322	Slab No. A622	Slab No. P22
Cycle Rating	Cycle Rating	Cycle Rating	Cycle Rating	Cycle Rating	Cycle Rating
No.	No.	No.	No.	No.	No.
1	1	1	1	1	1
2	2	2	2	2	2
3	3	3	3	3	3
4	60% L to HS	4	40% F.S.	4	15% F.S.
5	100% L to HS	5	80% F.S.	5	50% F.S.
6	6	6	100% F.S.	6	80% F.S.
7	100% M to HS	7	100% L.S.	7	40% M.S.
8	100% H.S.	8	100% F.S.	8	60% H.S.
9	9	9	100% M.S.	9	85% H.S.
10	10	10	10	10	100% H.S.
11	100% M to HS	11	100% L.S.	11	
12	12	12	100% L to MS	12	
13	13	13	13	13	
14	10% H.S.	14	100% H.S.	14	100% F to LS
		15	100% M.S.	15	100% L.S.
		16	16	16	
		17	100% H.S.	17	100% L to MS

Table 27. Set 2 Scaling Tests



Slab No. ENM1			Slab No. ED31			Slab No. ED61			Slab No. EDB		
Cycle No.	Rating	Cycle No.	Rating	Cycle No.	Rating	Cycle No.	Rating	Cycle No.	Rating	Cycle No.	Rating
1		1		1		1		1		1	
2		2		2		2		2		2	
3	100% F.S.	3		3		3		3		3	
4		4		4		4		4		4	
5		5	100% F.S.	5		5		5		5	
6	100% L.S.	6	100% L to FS	6		6		6		6	
7	100% M to HS	7	100% L.S.	7		7	75% F.S.	7		7	
8	100% H.S.	8		8		8		8		8	
		9	100% M to HS	9		9	100% L to MS	9		9	
		10	100% H.S.	10	100% F.S.	10		10		10	
		11		11		11		11		11	
		12		12		12		12		12	
		13	100% F to IS	13		13		13		13	
		14		14		14		14		14	
		15		15		15		15		15	
		16		16		16		16		16	
		17		17		17		17		17	
		18	100% L.S.	18	100% L to MS	18		18		18	

Table 28. Set 3 Scaling Tests



## Discussion of Results

Results from the scaling tests show clearly an increased resistance of concrete to scaling due to entrained air. This resistance increases with increases in air contents for the range of air contents used in the investigation.

Slabs with air contents ranging from 4.5% to 7% were found to have at least twice the resistance of the normal concrete. The pozzolith mixes with air contents of around 2% were found to have little or no increase in resistance to scaling as compared to the normal mix. This could be due to the fact that only small amounts of air are entrained by pozzolith. Another possibility is that the calcium chloride which is added to pozzolith as an accelerator exerts a detrimental effect on the durability of the concrete. This possibility is discussed further under freeze-thaw test results. Mixes having air contents of 2% to 4% were found to have approximately 50% to 100% more resistance to scaling than normal concrete.

Two types of scaling were found to occur. One in which the mortar slowly scales away gradually exposing the coarse aggregate. This type of scaling generally occurred on air-entrained slabs. On slabs of Set 2 and Set 3 this type of scaling progressed rapidly until the slabs were 100% medium scaled. After this stage was reached scaling cycles were found to have very little effect on the surface. This occurred only with the slabs having air entrained by Darex and Ayr-Trap. The second type of scaling is the case where the whole top layer of the slab, to a depth of  $\frac{1}{8}$ " to  $\frac{1}{4}$ ", loosens and scales away in large pieces. As much as 70% heavy scaling can occur this way after a scaling cycle. This type of scaling was very evident with the normal slabs. Three out of four of the pozz-



olith slabs also scaled in this manner. A few other air-entrained slabs also scaled this way but an increased resistance to scaling was still evident. The top layer of the slab tended to heave and break the bond with the rest of the slab. This bond failure occurred as a rule where the first concentration or layer of coarse aggregate existed. This heaving of the top layer is probably due to the alternate freezing and thawing which takes place only in the top layer of the slab. The air-entrained slabs, because they are less permeable and also because they contain these tiny entrained air bubbles, are more capable of absorbing the stresses and strains caused by the scaling cycles.

The first type of scaling proceeded on the slabs made with Elk Island sand. The change in sand had no noticable effect on the resistance of the normal concrete to scaling. However, the 6% Darex mix slab is holding up well and much longer than any similar mix using washed Doncaster sand. The tests are too limited, however, to show any pronounced effect of sand type on the resistance of concrete to scaling.

In several cases scaling was found to start in the form of popouts over coarse aggregate. This seems to be caused by the expansion of the free water in the concrete on freezing, which breaks the bond between the surface paste and the coarse aggregate. This occurs only where the coarse aggregate is very close to the surface.

On comparing these scaling tests with those conducted by the Portland Cement Association <sup>9,10</sup>, our slabs were found to have scaled

9

Proceedings of American Concrete Institute, Vol. 33, 1937.  
Effect of Calcium and Sodium Chlorides on Concrete When Used for Ice Removal, by H.F. Gonnerman.

10

Proceedings of the American Concrete Institute, Vol. 39, 1943.  
Influence of Sands, Cements, and Manipulation upon the Resistance of Concrete to Freezing and Thawing, by W.C. Hansen.



very rapidly. The only difference between the two series of tests is that the Portland Cement Association carried out the scaling tests on a troweled surface. Further tests comparing these two surfaces would be very interesting.



## CHAPTER VII

FREEZING AND THAWING TESTSTesting Procedure

The specimens,  $3\frac{1}{2}$ " x  $4\frac{1}{2}$ " x 16" beams, were subjected to reversals in temperature from 55° F to 5° F. Eleven cycles were completed every 24 hours. The first series of beams were put in the freeze-thaw unit at an age of 28 days. This practice could not be continued for later sets of beams because of the large number of cycles required to break down some of the beams. The modulus of elasticity of the concrete was determined dynamically (Sonic test) just prior to the freezing and thawing test. The values obtained are given in Table 29. Other values of the modulus of elasticity were obtained after every 11 cycles of testing except on weekends when 23 cycles elapsed before another set of readings were taken.

The durability factors (DFE) of all beams tested are given in Table 30.

A review of literature on previous investigations dealing with air-entrained concrete failed to disclose a durability factor which takes into account the loss in weight of beams undergoing cycles of freezing and thawing. In an effort to correlate the effect of air entrainment on loss in weight due to cycles of freezing and thawing a durability factor (DFW) based on the loss in weight is used. It is calculated by use of the following formula:

$$DFW = \frac{BX}{Y}$$

where DFW = durability factor in percent of the original weight of beam at 0 cycles.

X = percent of original weight of 90 percent or greater



X = number of cycles at which R reaches 90 percent  
or the ultimate number of cycles

Y = Ultimate number of cycles of test

The durability factors (DFW) of all beams tested are given in Table 31.

A more rigorous evaluation would have to take into account the actual area under the curves obtained by plotting % original weight vs. cycles of freezing and thawing.



TABLE 29  
DYNAMIC MODULUS OF ELASTICITY OF CONCRETE

C.F. = 5 bags/cubic yard		
Admixture		Dynamic Modulus of Elasticity psi x 10 <sup>6</sup>
Pour 1		28 day curing
Mix 1	NM1	
	D31	4.97
	D61	4.41
	A31	4.85
	A61	4.91
	P1	5.12
Pour 1		28 day curing
Mix 2	NM2	
	D32	4.58
	D62	4.51
	A32	4.66
	A62	4.63
	P2	5.12
Pour 2		31 day curing
Mix 1	NM1	4.97
	D31	5.15
	D61	4.81
	A31	5.42
	A61	5.28
	P1	5.97
Pour 3		41 day curing
	ENM	5.18
	ED3	5.20
	ED6	4.70
	ED8	4.72



### Test Results

The influence of the various admixtures on the resistance of concrete to rapid freezing and thawing is summarized in Tables 30 and 31, in terms of durability factors. A series of pictures were taken of the beams in order to show the effect of cycles of freeze-thaw on the various concrete mixes. (See Figures 39 to 48). The history of the decrease in Dynamic E and of the decrease in weight of the specimens is shown in Figures 49 to 56.



Figure 39.



Figure 40.





Figure 41.



Figure 42.



Figure 43.





Figure 44.

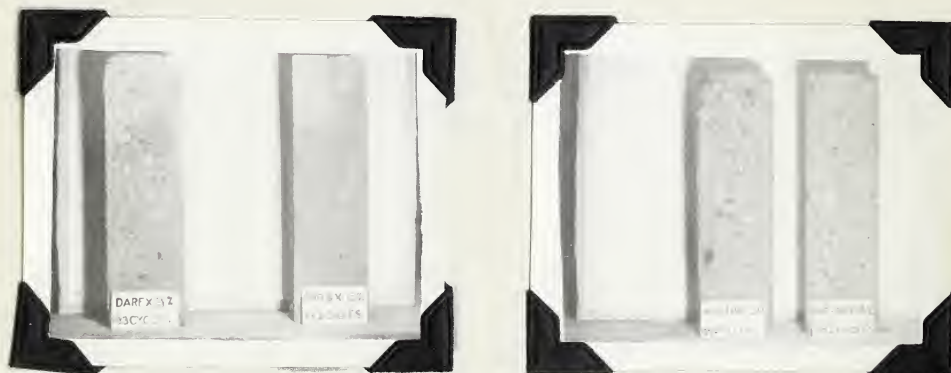


Figure 45.



Figure 46.



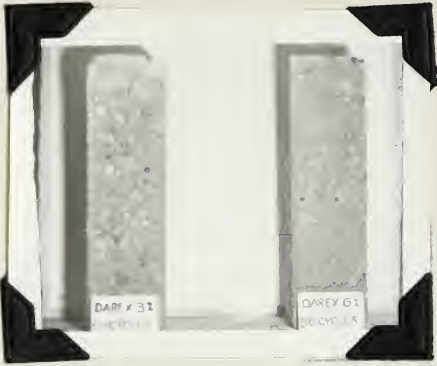


Figure 47.

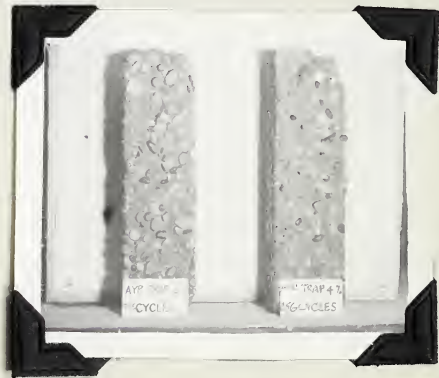
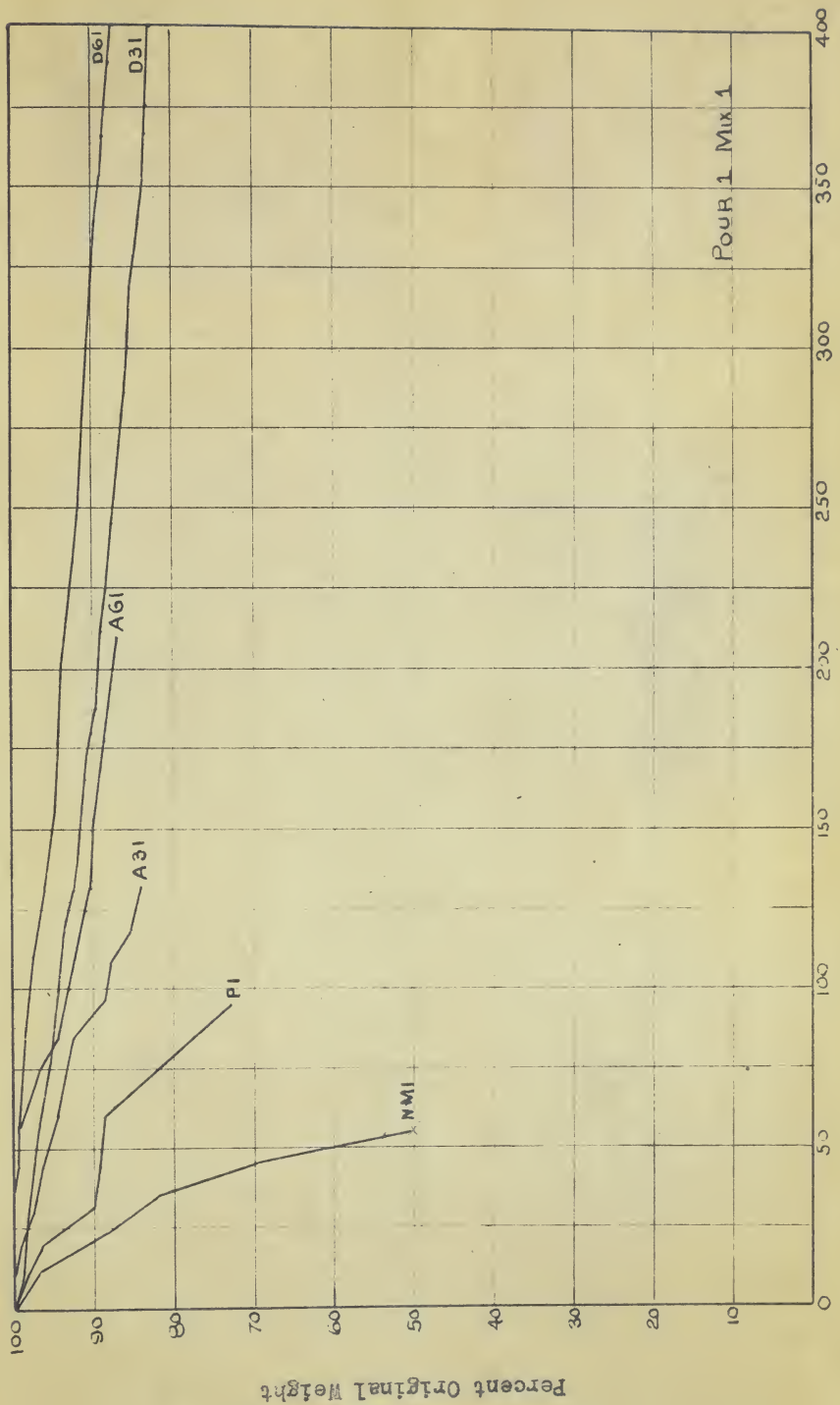


Figure 48.

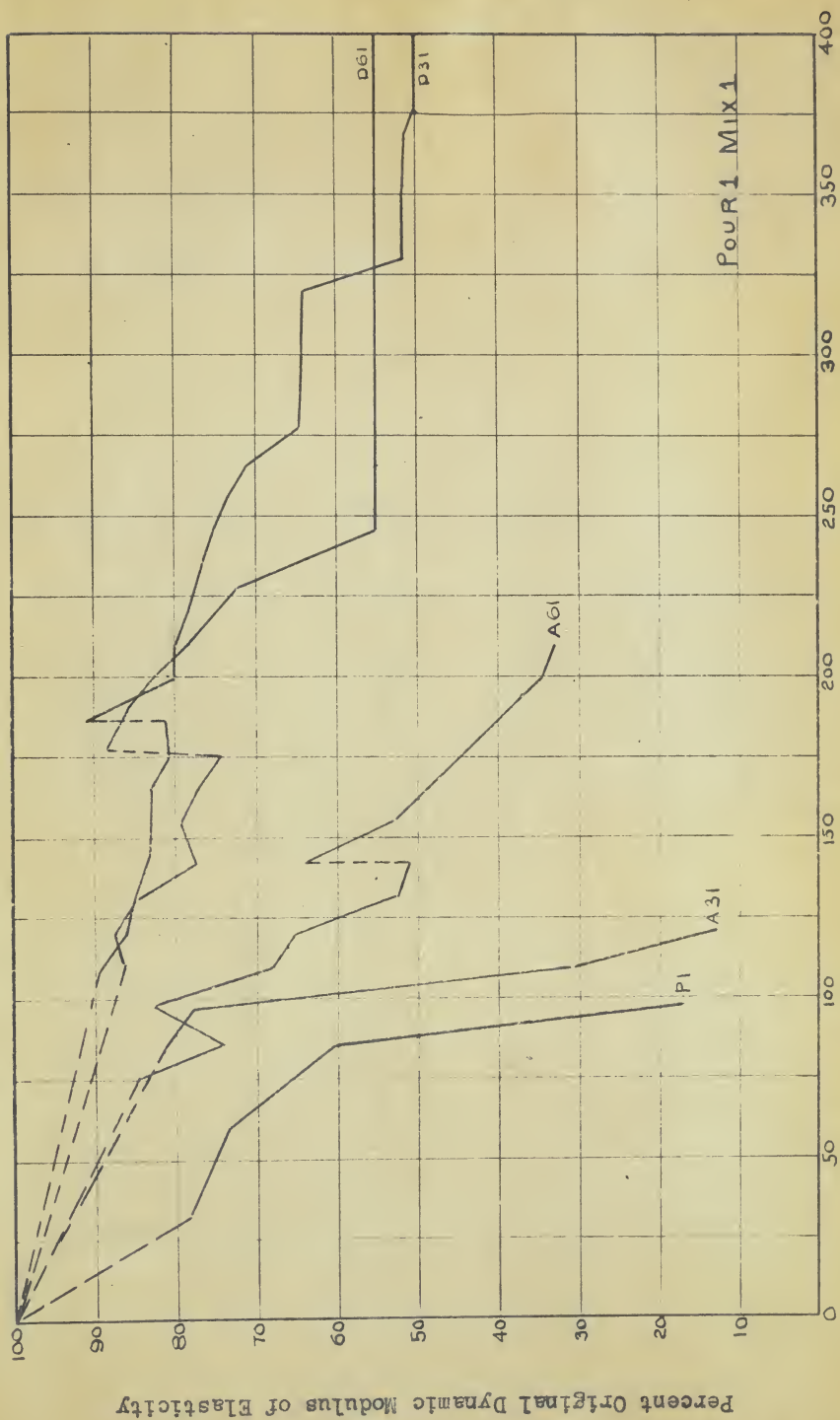




Cycles of Freezing and Thawing

Figure 49





Cycles of Freezing and Thawing

Figure 50



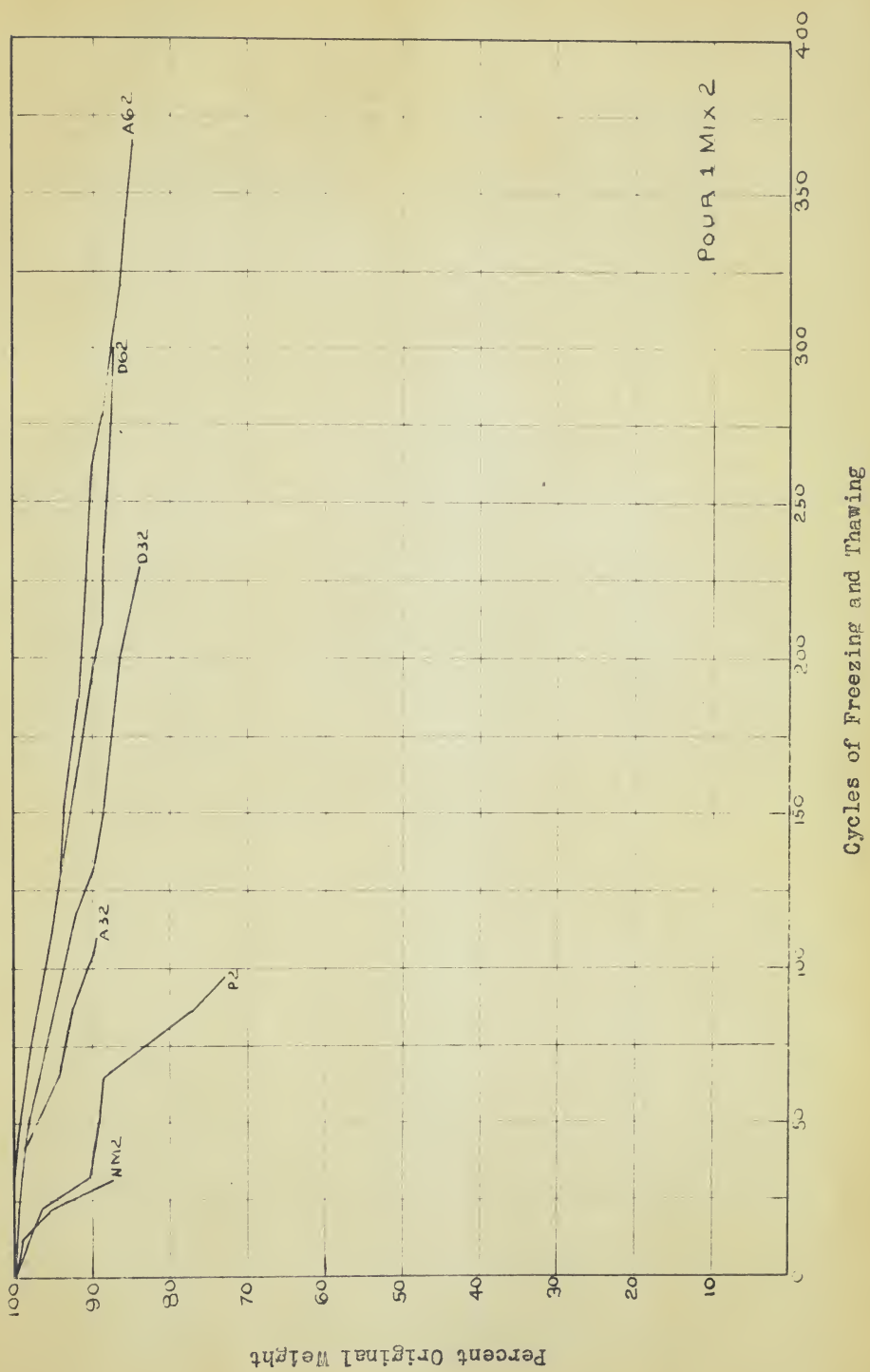


Figure 51

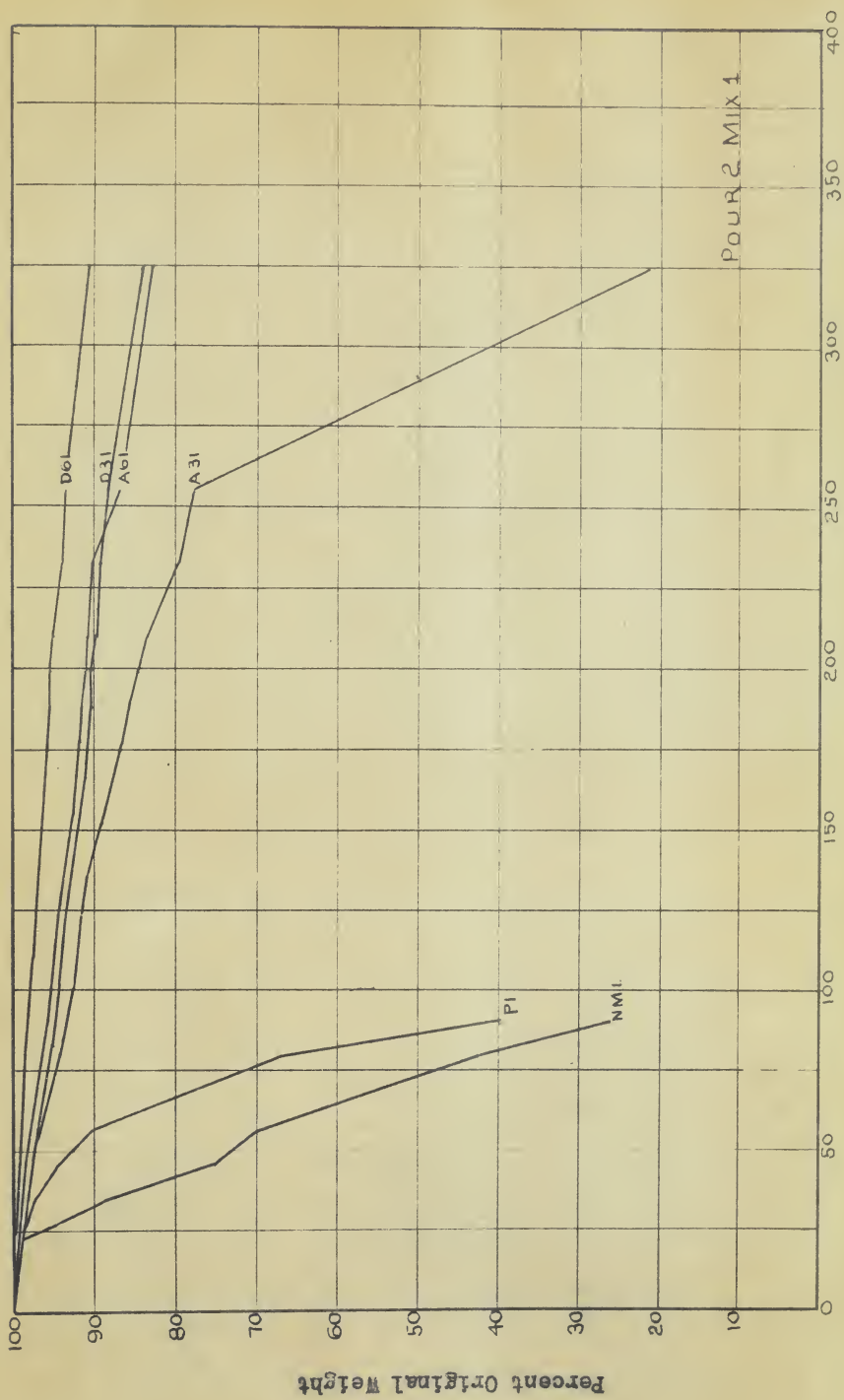




Cycles of Freezing and Thawing

Figure 52

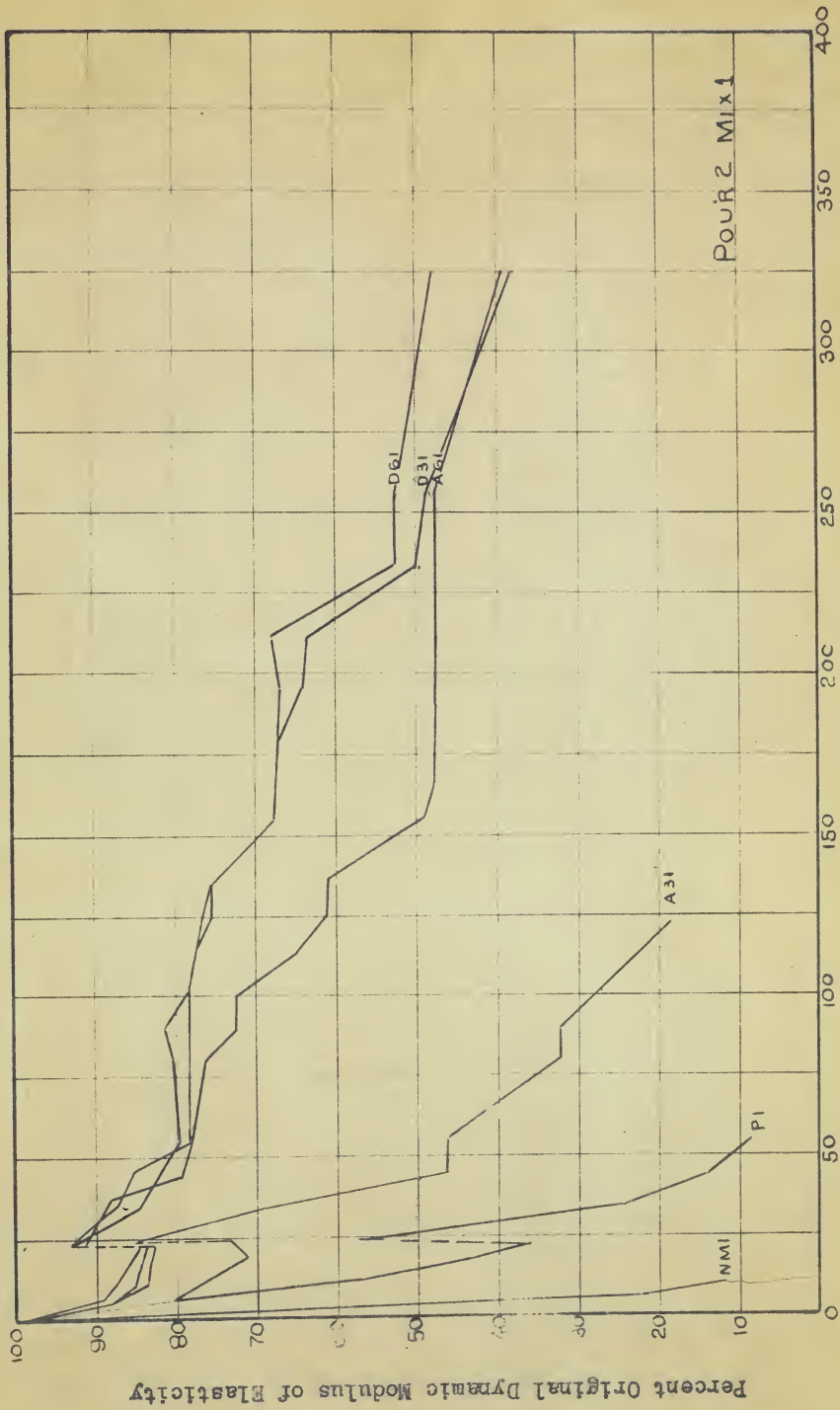




Cycles of Freezing and Thawing

Figure 53

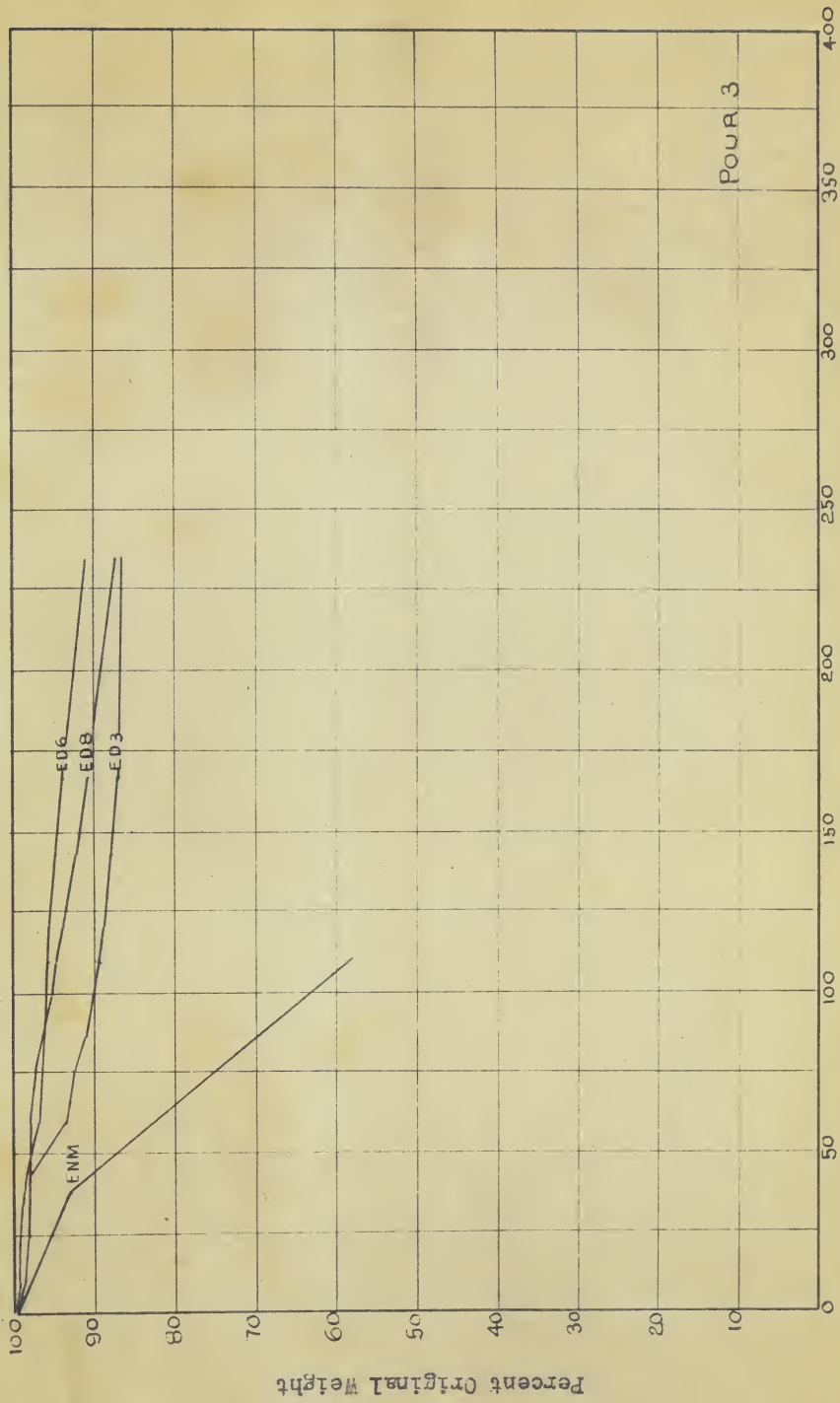




Cycles of Freezing and Thawing

Figure 54

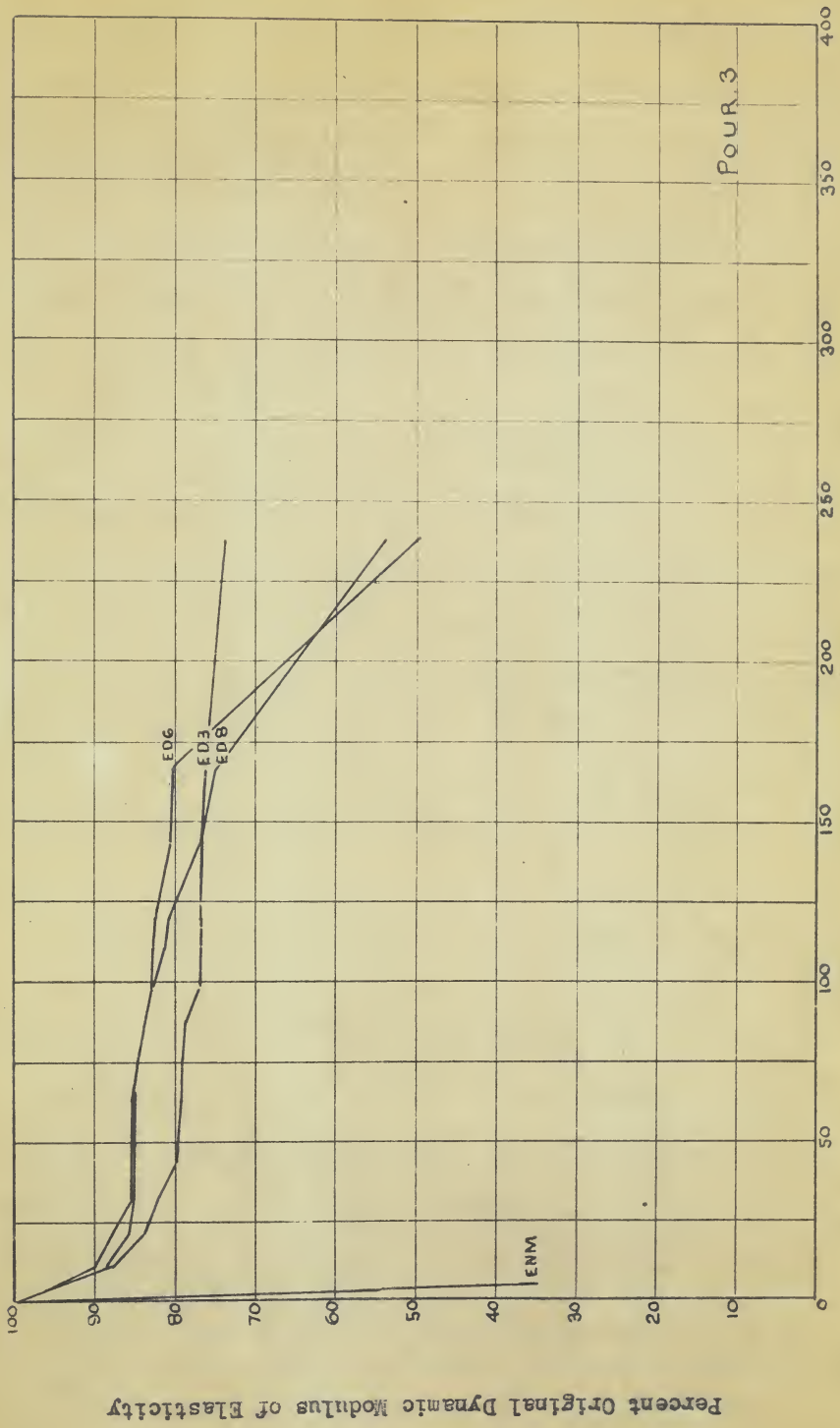




Cycles of Freezing and Thawing

Figure 55





. Cycles of Freezing and Thawing

Figure 56



## Discussion of Results

The history of the decrease in dynamic modulus of elasticity and of the decrease in weight of the specimens is shown in Figures 49 to 56. The beneficial effect of air entrainment is very evident. This beneficial effect increases with the air content for the range of air contents used in the investigation.

One percent entrained air increased the durability of concrete as indicated by the durability factor DFE by some 2000 percent. Entrained air contents of from 4 to 5 percent gave increases ranging from 12,000 to 20,000 percent. These remarkable increases are possible because of the fact that the normal mix had a very low durability factor. This low durability factor is probably due to the coarse aggregate. This is suggested by a comparison of results with those of an investigation carried out by Charles E. Wurpel<sup>11</sup>. It is also evident from Wurpel's work that the coarse aggregate is the controlling influence on the durability of concrete mixes as evaluated by the modulus of elasticity. Air entrainment seems capable of equalizing the relative durability of mixes containing highly durable aggregate and mixes containing non-durable aggregate.

The durability factor (DFW) seems capable of evaluating the effect of fine aggregate on the durability of concrete subjected to cycles of freezing and thawing. The fine aggregate would have a controlling influence on losses in weight due to the freeze-thaw action. Test results indicate the loss in weight due to cycles of freeze thaw to be directly related to the air content, the loss in weight decreasing with increases in air content. Entrained air contents of one percent were found to give

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<sup>11</sup> Automatic Accelerated Freezing-and-Thawing Apparatus for Concrete, Proc. A.S.T.M. Vol. 45, 1945, by Charles E. Wurpel and Herbert K. Cook.



TABLE 30

RESISTANCE OF CONCRETE TO FREEZING AND THAWING  
EXPRESSED AS DURABILITY FACTOR (DFE) AT 250 CYCLES

		Admixture	% Air	Durability Factor (DFE) <sup>E</sup>
Pour 1		Cured 28 days		
Mix 1	NM1		1.55	
	D31		4.05	80
	D61		6.6	88
	A31		3.4	21
	A61		5.0	32.3
	P1		2.7	17.6
Pour 1		Cured 28 days		
Mix 2	NM2		1.50	
	D32		4.10	47
	D62		6.7	52
	A32		2.7	18
	A62		5.2	74
	P12		2.1	19
Pour 2		Cured 31 days		
Mix 1	NM1		1.1	0.40
	D31		3.0	46.4
	D61		6.1	59
	A31		2.1	8.5
	A61		4.0	31.0
	P1		2.0	3.0
Pour 3		Cured 41 days		
	ENM		1.25	.40
	EB3		3.6	69
	ED6		6.2	47.4
	ED8		7.5	51.2



TABLE 31  
RESISTANCE OF CONCRETE TO LOSS IN  
WEIGHT CAUSED BY FREEZING AND THAWING  
EXPRESSED AS DURABILITY FACTOR (DFW)  
AT 250 CYCLES

Admixture		% Air	Durability Factor (DFW)
Pour 1			Cured 28 days
Mix 1	NM1	1.55	7.2
	D31	4.05	65.0
	D61	6.6	117.0
	A31	8.4	32.4
	A61	5.0	47.0
	P1	2.7	10.8
Pour 1			Cured 28 days
Mix 2	NM2	1.5	10
	D32	4.1	46.8
	D62	6.7	71.3
	A32	2.7	37.8
	A62	5.2	94.4
	P2	2.1	11.5
Pour 2			Cured 31 days
Mix 1	NM1	1.1	12.6
	D31	3.0	72.8
	D61	6.1	119.0
	A31	2.1	52.0
	A61	4.0	82.6
	P1	2.0	20.5
Pour 3			Cured 41 days
	ENM	1.25	16.2
	ED3	3.60	36.6
	ED6	6.20	90
	ED8	7.50	65



increases in durability of from 100 percent to 400 percent. Entrained air contents of from 4 to 5 percent gave increases of from 900 percent to 1500 percent. No appreciable difference in durability due to type of fine aggregate used was evident. The normal mix using Elk Island sand being some 25 to 50 percent more durable than the mixes containing Doncaster washed sand. However, the entrained air mixes using Elk Island sand are not as durable as the entrained air mixes using Doncaster washed sand. In evaluating results it becomes evident that a standard procedure for casting the specimens is required. The amount of surface finishing and spading probably having an appreciable effect on the losses in weight due to freeze-thaw cycles. All specimens cast for the investigation were rodded and spaded under a standardized procedure.

A comparison of mixes P1 and A31 of Pour 2 indicates the effect the admixture itself can have on the durability of concrete. Both mixes have air contents of 2 percent. The durability factor DFE indicates comparable durability with regard to loss in modulus of elasticity. However the durability factor DFW indicates the A31 mix to be some 350 percent more durable with regard to loss in weight. A possible explanation is that the calcium chloride added to the pozzolith as an accelerator causes the more rapid loss in weight.

An interruption of a few days in the accelerated freeze-thaw process was found to allow the concrete to recover varying percentages of the modulus of elasticity. The percentage recovered varied from mix to mix and is probably dependent on such variables as time of recovery, age of specimen, air content, strength, and reduction in modulus of elasticity before recovery period. This recovery between cycles of freeze-thaw could definitely be a factor in correlating the laboratory results with field service results.



## CHAPTER VIII

SUMMARY AND CONCLUSIONSSummary

An evaluation of air-entrained concrete was made based on the effect of air entrainment on the properties of plastic concrete mixtures and the durability and strength of hardened concrete. The durability of the concrete was evaluated by determining its resistance to scaling action and cycles of freezing and thawing. The effect of the entrained air on the strength of concrete was determined by cylinder compression tests and beam flexural tests.

Conclusions

1. An appreciable increase in workability was noted in the air-entrained mixes as compared to the normal mix at equal slump and flow. This increase in workability was noted in the absence of segregation, the reduced bleeding of poured cylinders, and the increase in rodability and finish ability of the air-entrained mixes. The air-entrained mixes proved to be considerably more cohesive and plastic than the normal mix.
2. In all but a few cases the air entraining admixtures added had a beneficial effect on the compressive strength of the concrete. This beneficial effect decreased with age being practically zero at an age of 3 months. The admixtures used were found to have little or no detrimental effect on the flexural strength of the concrete.
3. An appreciable increase in resistance to scaling caused by using calcium chloride for ice removal was noted in the air-entrained mixes. This resistance increased with increases in air contents. Air contents of 4 to 6 per cent were found to



increase the resistance to scaling from 200 to 300 per cent. Pozzolith added in quantities suggested by the manufacturer had little or no beneficial effect on the resistance of the concrete to scaling.

4. Air entrainment increased the durability of concrete to a remarkable extent. The effects of cycles of freezing and thawing on concrete beams was evaluated by durability factors dependent on relative losses in the modulus of elasticity of the concrete and losses in weight of the concrete beams. Entrained air contents of 4 to 5 per cent increased the resistance of the concrete to loss in weight by some 900 to 1500 per cent and its resistance to losses in modulus of elasticity by some 12000 to 20000 per cent.



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1. The first part of the paper is devoted to a general

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2. The second part is devoted to the study of the

properties of the functions which are considered.

3. The third part is devoted to the study of the

asymptotic behavior of the functions.

4. The fourth part is devoted to the study of the

convergence of the series.

5. The fifth part is devoted to the study of the

properties of the functions.

6. The sixth part is devoted to the study of the

asymptotic behavior of the functions.

7. The seventh part is devoted to the study of the

convergence of the series.

8. The eighth part is devoted to the study of the

properties of the functions.

9. The ninth part is devoted to the study of the

asymptotic behavior of the functions.

10. The tenth part is devoted to the study of the

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